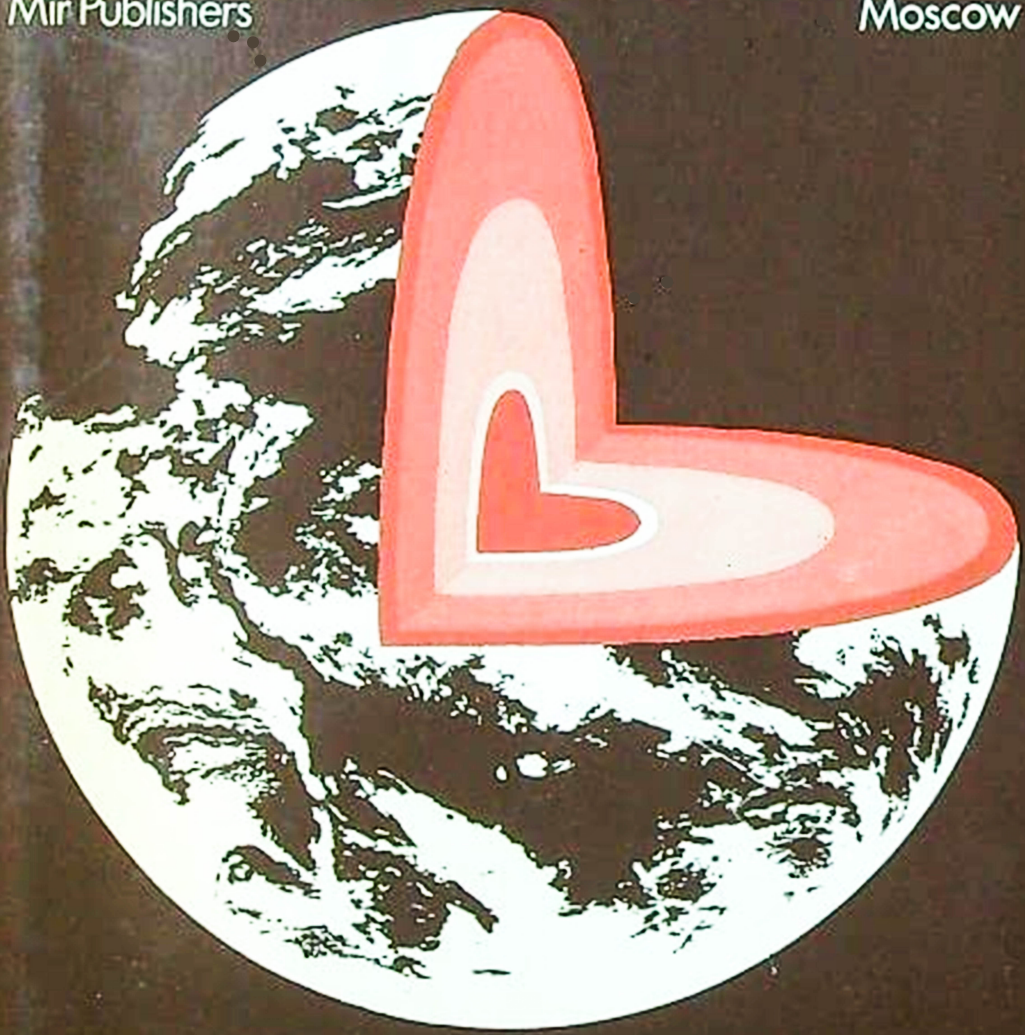
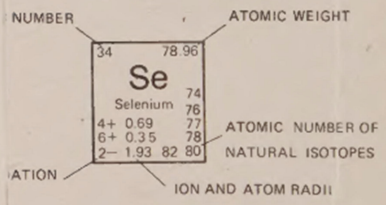
Fundamentals of GEOLOGY

V. V. Ershov, A. A. Novikov, and G. B. Popova

Mir Publishers Moscow



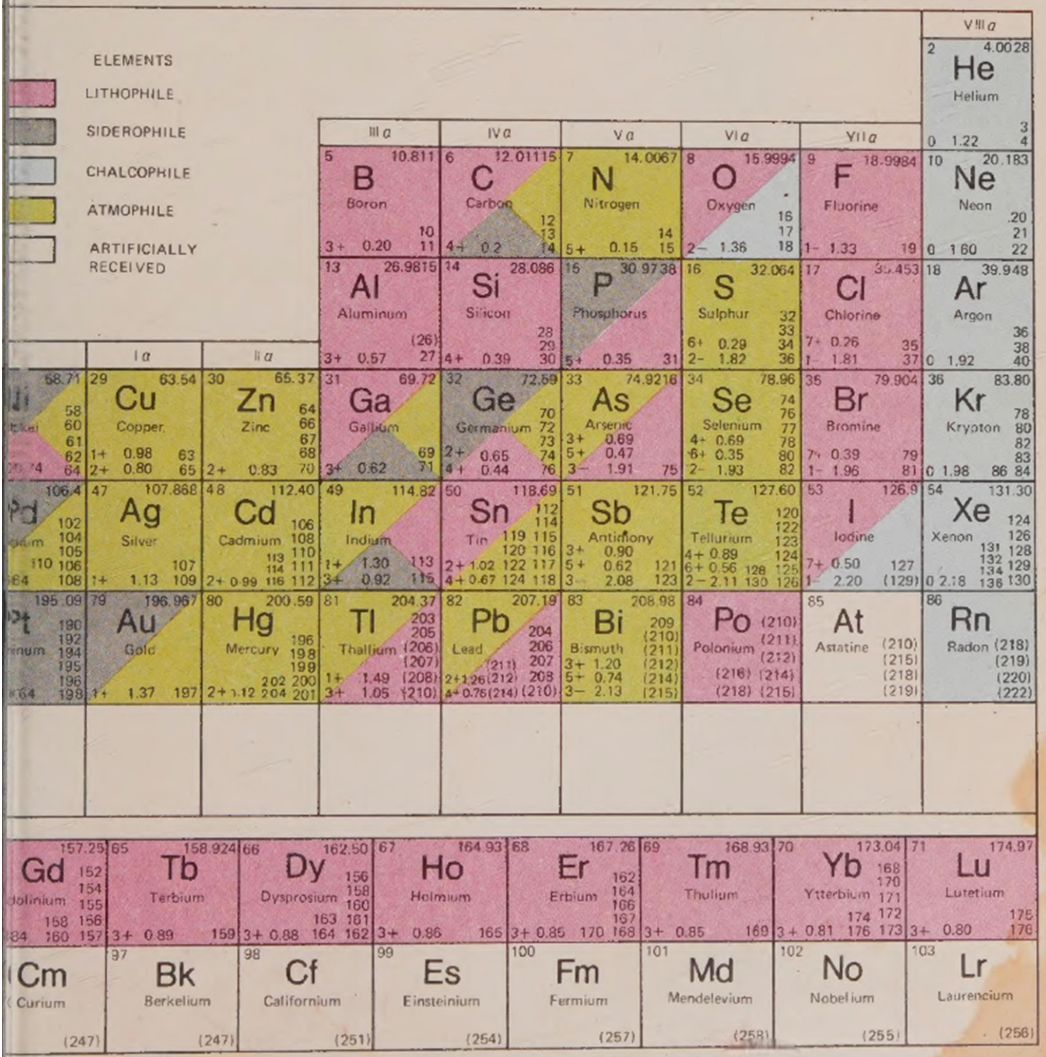
This textbook is a comprehensive compendium of the research that has been carried out by its authors and their vast teaching experience within the period of many years. It is intended for the students of higher educational institutions whose future profession is not immediately connected with geology. Hence every effort has been made to make the manual comprise only the most essential information on the subject and present it in a form that would be as precise as possible and at the same time lack any simplifications that could reduce its scientific validity. The book consists of six parts from which the student will derive a sufficient knowledge concerning the structure of the earth's crust, endogenic and exogenic processes, tectonics, etc. Particular stress has been laid on presenting the material in compliance with the currently important tasks set by the science of mining engineering and mining industry.



	V b	VI b	VII b	VIII b	
	50.942 **V** Vanadium 0.72 0.67 0.61 50 0.41 51	24 51.996 **Cr** Chromium 50 2+ 0.83 52 3+ 0.64 53 6+ 0.35 54	25 54.938 **Mn** 2+ Manganese 3+ 0.91 4+ 0.70 7+ 0.52 0.46 55	26 55.847 **Fe** Iron 54 56 2+ 0.80 57 3+ 0.67 58	27 58 **Co** Cobalt 2+ 0.7 3+ 0.6
	92.405 **Nb** Niobium 0.67 0.66 93	42 95.94 **Mo** Molybdenum 92 94 95 4+ 0.68 96 98 6+ 0.65 100 97	43 **Tc** Technetium (99)	44 101.07 **Ru** Ruthenium 96 98 99 100 104 101 4+ 0.62 102	45 **Rh** Rhodi 3+ 0.7 4+ 0.6
	180.948 **Ta** Tantalum 180 0.66 181	74 183.85 **W** Tungsten 180 182 183 4+ 0.68 184 6+ 0.65 186	75 186.2 **Re** Rhenium 185 6+ 0.52 187	76 190.2 **Os** Osmium 184 186 187 188 190 189 4+ 0.65 190	77 **Ir** Iridiu 4+ 0.6
	5 **Ns** Nilsborium (261)				

LANTHANIDES	57 138. **La** Lanthanum 3+ 1.04 138 4+ 0.90 139	58 **Ce** Cerium 136 138 3+ 1.02 140 4+ 0.88 142	59 **Pr** Praseodymium 3+ 1.00 141	60 144.24 **Nd** Neodymium 142 143 144 148 145 3+ 0.99 150 146	61 **Pm** Promethium 3+ 0.98 (145)	62 150.35 **Sm** Samarium 144 147 148 152 149 3+ 0.97 154 150	63 **Eu** Europ 2+ 1.19 3+ 0.97
ACTINIDES	89 **Ac** Actinium (227) 3+ 1.11 (228)	90 232.038 **Th** Thorium (227) (228) (230) 3+ 1.08 (231) 4+ 0.95 (234) 232	91 **Pa** Protactinium 3+ 1.06 (231) 4+ 0.91 (234)	92 238.03 **U** Uranium (234) 3+ 1.04 235 4+ 0.89 238	93 **Np** Neptunium 3+ 1.02 4+ 0.88 (237)	94 **Pu** Plutonium 3+ 1.01 4+ 0.86 (244)	95 **Am** Americi

V. Goldschmidt divided all chemical elements into groups according to stability of different types of their compounds existing in nature. His classification was based on the distribution laws of elements by three main phases of meteorites: silicate (oxygen), sulphide, and metallic. Lithophile (enriching the silicates), chalcophile (enriching the sulphides) and siderophile (enriching the metallic phase) elements are consequently distinguished. Moreover, V. Goldschmidt distinguished the atmophile elements which are characterized by a gaseous state in the Earth's surface conditions and their accumulation in the atmosphere.



Fundamentals of GEOLOGY

В. В. Ершов, А. А. Новиков, Г. Б. Попова

ОСНОВЫ ГЕОЛОГИИ

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V.V. Ershov A.A. Novikov and G.B. Popova

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Preface

Geological education is one of the most important elements in the training of a modern mining engineer, a broad specialist who, given the ever more complicated conditions in the field, is capable of solving problems related to the effective development of the depths of the Earth. Geology is the comprehensive study of the environment with which the mining industry is concerned. It provides the key to the understanding and forecasting of the conditions in which mining operations are conducted. Further scientific and technical progress in the mining industry becomes impossible without a comprehensive analysis of the natural conditions pertinent to the development of deposits.

Geology, as a scientific and industrial branch of the national economy, provides a more advanced development of the mineral and raw material basis for various branches of industry and agriculture. The role of geological studies at the present-day stage of the scientific and technical revolution becomes even greater in connection with finding solutions to the problems of environment protection and the rational use of the depths of the Earth and natural resources on the whole. Since the negative impact resulting from man's transformation of the environment is continually increasing and has reached a global scale, the ecological problem and the optimization of the interrelationship between man and nature have proved to be the most important aspects of scientific and technical activity.

The whole variety of geological information for students of mining specialities is presented in a series of geological courses among which 'Fundamentals of Geology' plays the leading role. 'Fundamentals of Geology' is not merely an introductory course, or some kind of 'geological alphabet'. It embraces the general methodology of geological sciences together with the structural and developmental regularities of the whole geological environment and its individual elements: these are the subjects and objects to which mining and technological research and work are confined.

Having taken into account the specific features relevant to the geological training of students of mining specialities, the authors lay particular stress on the treatment of the structural and compositional regularities of geological objects of various levels. The tectonic zonation and geological structure of continents and oceans is discussed in greater detail and special attention is given to the assessment of those conditions that are most important for the localization of deposits of mineral resources, to the development of which the activity of future mining engineers will be devoted. The textbook contains a brief outline of the geological and structural features of the USSR, since, as was stated by Academician N. Shatsky, 'the vast territory of our country provides ample

opportunities to solve all the most vital problems concerning the structure and development of the earth's crust.'

The discussions about geological processes emphasize their results – the geological objects – as well as the processes and phenomena, which must be considered when mining operations are in progress. In the disquisition of geotectonic hypotheses and a number of other disputable genetic constructions, the authors have made every effort to be as objective as possible and present various points of view in relation to the facts presented in the textbook. The authors have also suggested a generalized model of the development of the lithosphere, in which the traditional geosynclinal concepts are coordinated with the recent geotectonic ones, while the whole variety of geological processes has been treated in terms of dialectical interrelationship and historical succession.

In the textbook the student will find information on the construction principles and on the methods of the practical application of geological graphical materials in the study of the earth's crust. A special part of the textbook has been allotted to technogenic problems, including problems connected with the mining industry and changes of the geological environment under the influence of man.

When the original manuscript (the Russian version) was being prepared for publication the authors carefully reviewed previous experience in the teaching of general geology and adjacent courses to students of geology in the Soviet Union and what was already expounded in the widely known textbooks by G. Gorshkov, A. Yakushova, M. Zhukov, V. Slavin, V. Serpukhov, A. Mikhailov, V. Milnichuk, and others. The authors have also availed themselves of the nontraditional approach and principles of teaching methods. In the preparation of the present manual in English the original Russian edition was considerably revised and amended with new data, genetic constructions and achievements in methods as contained in the well-known books on general geology by J. Allison, D. Palmer, M. Breadshow, P. Kennet, C. Ross, E. Larson, P. Birkeland, D. Coates.

The book has been written in the form of a textbook for students of higher educational institutions in the mining specialities and it is quite natural that it lacks some of the details essential for the training of geologists. However, it does contain information that will be of interest to both young and the mature geologists, as well as to mining engineers.

The Preface, Introduction, Chapters I-III and XVI-XXIII were written by V. Ershov. The authors of Chapters XII-XV are A. Novikov and V. Ershov. G. Popova has contributed Chapters IV-XI. The manuscript was prepared for publication by A. Gorbatova, L. Markova, and N. Smirnova to whom the authors wish to express their acknowledgements.

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Introduction

Our planet can be studied from very diverse points of view, hence there are few sciences that would have such a broad scope...

E. HAUGE

Subject, Tasks, and Methodology of Geological Studies

Geology is one of the most important natural sciences. It studies the structure, composition, origin and development of the Earth. The scope of its analysis includes statistical phenomena and dynamic processes that manifested themselves in the past and are taking place on our planet today. The present-day geology, equipped with special methods and vast experience of the study of the Earth, is by all means a synthetic science. It is very closely connected with other sciences investigating the Earth, e.g. astronomy, geodesy, geography and biology. What lies at the bottom of the research carried out by geologists is the knowledge of such fundamental sciences as mathematics, physics, and chemistry.

As distinct from other sciences studying our planet, geology concerns itself with the investigation of the depths of the Earth. The main task of this science consists in analyzing the outer stone sphere of the planet called *the earth's crust* and its interrelationship with the outer and inner spheres of the Earth. The outer spheres are known as the aerial one, or *the atmosphere*, the water medium referred to as *the hydrosphere*, and *the biosphere*, which contains the organic matter. Besides, it has recently become scientifically relevant to distinguish the *noosphere* – the space, within the confines of which the active impact of man upon nature finds its expression. The inner spheres of the Earth are *the mantle* itself and *the core*, which are inaccessible to direct observations, though their investigation is of vital importance for the understanding of a large number of processes occurring within the earth's crust.

The objects that lie in the domain of direct geological study include minerals, rocks, fossils of organic remains and geological processes. *Minerals* are defined as natural chemical compounds, which are homogeneous in their structure and composition and which are formed as a result of natural physicochemical processes. *Rocks* are the natural stable associations of minerals that have appeared as a result of some particular geological processes and that give rise to the formation of independent geological bodies within the earth's crust. According to their origin, rocks are divided into those that are *magmatic*, or *igneous*, i.e. the ones that emerged during the cooling of the liquid-molten silicate melt (magma); *the sedimentary* rocks that originated under mechanical, chemical or biochemical reworking of the substance of the earth's crust in surface conditions; and *metamorphic* rocks, which are formed during the process involving the transformation of any of the primary rocks in the depths of the Earth under the influence of high temperatures, pressure and chemically active substances. *The fossils of organic remains* make it possible to reconstruct the conditions that were relevant to the formation of enclosing rocks and determine their age.

The processes that alter the composition and structure of the earth's crust, as well as the relief of the earth's surface, are called *geological.* In accordance with the source of energy, the place and conditions under which geological processes occur, they are classified as either exogenic (developing from without) or endogenic (originating internally).

Exogenic geological processes are brought about by the activity of solar energy on the surface of the Earth. They find their expression in the alteration (*weathering*) of rocks, disintegration and the transportation of such products by water and air, and lastly, in their *sedimentation.*

Endogenic geological processes are developing owing to the inner energy of the Earth. They comprise *tectonic processes*, which bring together slow (age-long) oscillatory movements of the earth's crust and the fairly rapidly occurring *dislocation movements* which become responsible for the disruption of the initially deposited rocks; *magmatism* is the phenomenon, which is related to the formation of liquid-molten silicate melts in the depths of the Earth, their movements and solidification; *metamorphism* is expressed by profound changes that occur in rocks under the impact of high temperatures, pressures, and chemically active substances at depth in the earth's crust.

Geology refers to the domain of natural and historical sciences, and according to A. Werner, the German geologist of the 18th century, 'it embraces everything that we know of this Earth of ours'. It occupies an intermediate position between the sciences of outer space and those of the terrestrial group, between the sciences of inorganic and organic nature, between the sciences studying nature and human society. Geology deals with a concrete natural and historical system: it is *the geological form of matter in motion*, which is the product of the development of outer space systems; it is the environment and medium for the growth of organic nature, the productive forces of society and the prerequisite and condition for social progress.

The geological material system is characterized by its complexity and the multilateral organization of the substance, as well as by the laws acting in its structure, within the framework of a particular type of natural integrity, and the specific features of the development in space and time. This system represents a part of the material world and reflects in its structure its more substantial associations. There is every reason to say that without the data furnished by geology it would hardly be possible to regard the dialectical and materialistic concept of the development of nature as an integral universal process adequately valid in scientific terms.

The specific features of geology have long attracted the attention of representatives of different philosophical schools and trends. Geology has withstood a fierce struggle against religion, idealism, and the metaphysical approach; it has been accumulating scientific evidence for consolidating the dialectical and materialistic way of thinking. Since some time in the past the principles of dialectical materialism have become the one and only theoretical foundation for this science, thus stimulating its further progress.

In geology, as in the vast majority of other natural and historical sciences, the main role is allotted to *the historical approach.* It is firmly based on the historical principle, which presupposes the analysis of the phenomena under consideration

against the background of the patterns governing their appearance, development and disappearance taking into consideration the total factors conditioning the development in space and time.

What lies at the bottom of the scientific cognition of the geological history of the Earth, the reconstruction of processes and situations that go back to the remote past is *the method of actualism*. When this method is employed in order to properly apprehend the past, the study of present-day processes comes first, though with the understanding that in the past, particularly if considerable time has elapsed, both the physiogeographical situation and the processes themselves differed more from those occurring nowadays the more remote in time the epoch under our analysis is. The application of the actualistic method is found to be most effective in the field of sedimentary formation of rocks. This state of things can be accounted for by the fact that the contemporary sedimentary process has been studied in great detail and that its evolution in the history of the Earth is very slow.

In recent years a prominent role in geology has been played by *the systemic*, or *structural and functional, approach*, which, on the abstract level of the analysis of the material and energetic characteristic features of the system, concentrates on the laws of self-regulation and government.

Geology makes ample use of the direct, indirect, experimental and mathematical methods.

The direct methods include those that are connected with the investigations of the composition and structure of the earth's crust that are directly conducted on the Earth or at a distance (from troposphere and outer space). The principal method of geological research is *geological survey and mapping*. This method makes it possible to study the structure and the interrelationships of geological objects and processes, and is the basis for the exploration of mineral deposits.

Within the process of geological survey the evaluation of the composition and structure of the earth's crust is carried out by means of studying natural exposures (scarps of rivers, gorges, hillsides), workings (ditches, shafts, quarries, mines), and boreholes. At present, the maximum depth reached as a result of mining operations comprises 3.5-4 km (the mines in India and South African Republic). The deepest borehole in the world is in the Kola Peninsula. Its depth exceeds 12 km. Other individual boreholes have reached the depth of 8-9.5 km. Their average depth does not go beyond 4-5 km, which is 10 000 times less than the Earth's radius.

The indirect geophysical methods based on the investigation of natural and artificial physical fields created by the Earth on the whole and individual objects are abyssally much more prominent than the direct methods. According to the character of the physical properties and fields under analysis, there are *seismic*, *gravimetrical*, *electrical*, *magnitometrical*, and other methods.

The experimental researches in geology are directed at modelling of various geological processes (magmatism, metamorphism, tectonic processes and others) and the artificial recovery of various minerals and rocks.

The use of *mathematical methods and computers* in geology represents a particularly new but promising trend, the history of which does not cover more than 25 years. The development of this trend complies with the general tendency

of enhancing the efficiency, reliability and value of geological information. As has been mentioned by the well-known American specialist in the field of mathematical geology D. Edger, it is the expensive equipments and computers rather than the hammer that form the equipment of quite a few geologists today.

However, the use of mathematical methods and computers is confronted with serious difficulties. This can primarily be accounted for by the complexity of formalization and the ambiguity of geological concepts and definitions, insufficient quantitative study of the changes and the relationship between the geological objects under investigation.

Branches of Geological Sciences

Geology lends itself to a classification comprising scientific subjects studying the material composition of the earth's crust, its structure, geological processes and their historical sequence, as well as applied sciences.

The substance of which the earth's crust consists is studied by geochemistry, crystallography, mineralogy, petrography, and lithology. *Geochemistry* is the science which concerns itself with distribution and the processes of migration of chemical elements in the earth's crust and the Earth in general. *Crystallography* deals with the inner structure and form of crystals, while their composition, conditions of their formation and the regularities concerning their distribution constitute the subject of *mineralogy*. The study of rocks forms the domain of *petrography* and *lithology* (the scientific study of sedimentary rocks).

The contemporary structure and origin of the relief of the earth's surface are treated by *geomorphology*; *geotectonics* studies the development and structure of the earth's crust, while the form, arrangement and internal structure of the rocks are discussed by structural geology.

The general regularities of the processes related to the formation of the earth's crust are studied by *historical geology*. The history of the earth's crust is also analyzed in terms of *stratigraphy*, which considers the sequence in the formation and position of layered masses of rocks, and *paleontology*, studying the development of the organic world of the past geological periods.

Dynamic geology is the science of geological processes that includes such branches as *seismology* – the science of earthquakes, and *volcanology* – the scientific study of various manifestations of volcanism. A large section of geology concerned with the problems of the geological structure and development of individual regions is called *regional geology*.

Applied geological sciences comprise *the study of mineral deposits*, their prospecting and exploration; *hydrogeology*, the science dealing with the origin, composition, conditions of bedding and the movement of underground waters; *geological engineering* – the science of geological conditions pertinent to the emergence and exploitation of engineering structures. At present we may well be justified to speak of the development of the so-called *mining geology*. It is an applied geological science, which carries out the research into the geological maintenance of mining industry in planning, building, exploitation and liquidation of mining enterprises.

The Role of Geological Studies

The enormous significance of geology is related to its general scientific aspect and its economic value.

The importance of geology in sciences consists in its invaluable role in the formation of the materialistic understanding of nature. The data provided by geology play a highly important role in the dialectical and materialistic substantiation of the philosophical principles reflecting the material unity of the world and its development.

The function of geology in national economy finds its expression in providing its various branches with mineral and raw material resources, in the engineering and geological substantiation of the building of different kinds of civil and industrial objects, and in the solution of problems concerning the supply of drinking and technical water.

Particularly great is *the role of geology for mining sciences and industry*. In connection with the intensification of mining industry, the growing tendency of decreasing the quality of mineral raw materials and the complication of mining and geological conditions in which the deposits are developed, the problem of predicting these conditions acquires current importance, which can be brought into effect only on the basis of detailed geological investigations of the objects.

It should be pointed out that at present the mineral deposits in near the surface area of the earth's crust have already been discovered and are now being intensely developed. Hence, a more elaborate study of the deeper regions on the basis of a subsurface complex geological survey, mapping and exploration become of the first importance for applied geology.

The insufficiency of mineral reserves obtained from the depths of the Earth raises the problem of its extraction with minimal losses. The finding of more rational ways of exposing and developing the deposits call for the carrying out of detailed geological investigations. The problem that should be most urgently solved is connected with the complex use of mineral resources. Its solution rests entirely on the most profound study of the material that enters into the composition of the deposits.

Lastly, the application of new progressive methods employed for the recovery of mineral resources which include the subsurface leaching of ores (uranium, copper and gold), potash and rock salts, the underground melting of sulphur and the gasification of coals, the recovery of mineral resources from the floor of seas and oceans would be absolutely impossible without a clear-cut understanding of the geological structure of the objects that are developed, their material composition, as well as the information on the geological and physicochemical processes that take place within them.

The intensification of mining industry leads to its considerable concentration and the dislocation of huge masses of rocks. This causes marked disturbances in the natural equilibrium that has been attained within the period covering millions of years. The process of recovering mineral raw materials itself functions as one of the most powerful techtogene factors acting upon the earth's crust, the impact of which may well be compared with the activity of exogenic geological processes. In this connection, the geologists and mining engineers are at present

confronted with one more highly important *problem of sparingly utilizing natural resources*, which in itself is part and parcel of the general problem of protecting the environment.

The History of Geology (A Brief Outline)

The origin of geology goes back to ancient times. Ages B. C. man learnt to melt metals and make use of mineral water. From the very early days natural processes had always drawn the attention of man. However, the inauguration of geology as a science is regarded to have coincided with the second half of the eighteenth century – the period that was marked by the inception and violent development of the capitalist type of mining industry. F. Engels wrote that it had not yet relieved itself of the foetal stage, or mineralogy.

In Russia the first to make scientific geological generalizations was M. Lomonosov (1711-1765). In Western Europe the founders of the scientific study of the Earth were J. Hutton (1726-1797) and A. Werner (1750-1817).

M. Lomonosov advanced remarkable ideas concerning the formation of the relief of the earth's surface owing to the interaction of outer and inner forces; he calculated the thickness of the earth's crust and explained the origin of a large number of minerals and rocks. He also laid the foundation for the highly productive geological method of actualism and formulated the basic ideas of evolutional geology in his work 'On the Earth's layers' (1759), which were further elaborated by the English scientist Ch. Lyell.

In the process involving the struggle of geologists-evolutionists against the catastrophists (G. Cuvier, L. Buch, L. Elie de Beaumont), who rejected the idea of a gradual development of the Earth, and who interpreted the history of geological development in terms of periodically recurrent catastrophies, there emerged at the end of the eighteenth and the beginning of the nineteenth centuries such highly important scientific subjects as historical and dynamic geology. The evolutional ideas in geology were substantiated in the remarkable cosmogenic hypotheses of J. Kant and P. Laplace. The nineteenth century saw these ideas wholly consolidated.

The development of geology owes much to the discussion between the 'neptunists' (A. Werner) – who attributed the leading role of water to all geological processes and the origin of all the rocks on the bottom of water basins – and 'plutonists' (J. Hutton), who associated the 'subterranean heat' with all the transformations of the Earth and the formation of rocks. The scientific debate ended in 'plutonists' victory, which was based on the collection and analysis of copious new facts, that promoted the further development of geological studies.

The success achieved by geological mapping in the second half of the nineteenth century created the necessary prerequisites for geological generalizations concerning individual regions, countries and continents as a whole. The earth's crust was discovered to comprise two markedly different regions, viz. the mobile part (the so-called geosynclinal areas) and the stable 'rigid' (platform) part. The scientific study of geosynclinal and platform regions gave rise to the

emergence of geotectonics (J. Hall, G. Dana, A. Karpinsky, E. Suess, and others).

In 1875 the international organization of geologists – International Geological Congress – was initiated. Its periodic sessions were devoted to the discussions of the results of geological research carried out in different countries, and resolutions of general significance were adopted. Thus, special decisions were taken by the Congress on the unification of the content and design of geological maps, the nomenclature of rocks, the stratification of subdivisions, geological terminology, and so on.

At the same time, national geological societies began to appear in different countries. In Russia the Geological Committee was founded in 1882 (till that time there had existed since 1700 a special governing body for the management of prospecting and mining of mineral resources). The Committee widened its scope of planned activities on the geological surveying and mapping of the country's territory.

After the October Revolution (1917) geological research in the USSR has been conducted on an unprecedented scale. Within the first 20 years of the Soviet power 50% of the territory were subjected to geological exploration, which included 6% on the scale of 1 : 200 000, and the scale of 1 : 100 000 and more covering 2.8% of the whole territory. By 1983 maps on the scale of 1 : 200 000 had covered the whole territory of the Soviet Union (30% of the country's territory underwent mapping on the scale of 1 : 50 000).

The progress achieved in the development of all fields of geological studies and the creation of a firm mineral and raw material basis for all branches of national economy is considerably indebted to the research contributed by such outstanding scientists as A. Arkhangelsky, N. Belov, A. Betekhtin, Yu. Bilibin, V. Vernadsky, A. Vinogradov, I. Gubkin, F. Levinson-Lessing, V. Obruchev, S. Smirnov, N. Strakhov, M. Tetyaev, A. Fersman, N. Shatsky and the activity of many thousands of geologists carrying out practical work in this country.

I General Information on the Earth

The immence scales of Universe produces a feeling of insignificance on earthmen, and at the same time all the data received now give evidence of the Earth – a unique phenomenon within the confines of Solar System...

M. BRADSHAW

Chapter 1 The Earth as a Planet of the Solar System

Geology, as a science studying primarily our planet and its upper rock envelope, does not leave the surrounding material world, or *the Universe,* unheeded. This is conditioned by the fact that in the Earth's structure and development, there are certain features of similarity and dissimilarity with other planets; some of the geological processes are directly connected with cosmic phenomena.

The Structure of the Universe and the Solar System

The Characteristic Features of the Universe. The whole material world that surrounds us is called *the Universe*, or *cosmos*. The Universe is infinite both in space and time. Within the Universe the material is distributed irregularly and is represented by *stars, planets, dust, meteorites, comets,* and *gases*. The part of the Universe that is accessible to investigation is called the Metagalaxy and comprises over one billion groupings of stars, or *Galaxies*.

Milky Way Galaxy to which the Sun and the Earth belong refers to a spiral type and includes more than 150 billion stars. From the Earth, situated within the Galaxy, the Milky Way is seen in the form of a wide band of stars encircling the sky. The period during which the Sun and the stars rotate round the centre of the Milky Way makes 200-250 million years. The age of the Galaxy is approximately 12 billion years.

The Structure of the Solar System. The mass of the Sun comprises 99.87% of the whole mass of the system, while the mass of Jupiter – the largest of the planets – is 0.1%. Hence, the Sun is the centre of attraction of all cosmic bodies entering into the Solar System. All the bodies of the system are connected with the forces of gravity and, therefore, exert influence upon each other. According to its physical properties, the Sun represents a plasmic sphere. As has been established, the Sun consists of about 70 chemical elements of which hydrogen and helium are the most important ones. The diameter of the Sun is 109 times that of the Earth; the average density is 1.41 g/cm^3, the average temperature of the outer layers reaches 5 600 °C. The Sun is 5-5.5 billion years old.

The Sun's thermal energy is conditioned by the thermonuclear processes involving the transformation of hydrogen into helium. Within 1 s the Sun

radiates $4.2 \cdot 10^{26}$ J. Only 1/2-billion part of radiated energy falls on the Earth. The heat and light radiated by the Sun have an enormous impact on a large number of geological processes. The incessant explosive activity on the Sun causes the formation and dispersion into cosmic space of charged particles (ions and protons) which form the solar wind. The latter, in its turn, is connected with the emitting of lights and magnetic phenomena in the Earth's atmosphere.

The Solar System consists of 9 planets, 42 satellites, not less than 50 thousand small asteroids (planetoids), innumerable meteorites and hundreds of comets (Fig. 1). The Solar System is *coplanar*, i.e. the orbits of planets lie in one and the same plane, which coincides with the equatorial plane of the Sun, and have an almost circular form. The direction in which the planets rotate (except Venus and Uranus the rotations of which are reverse) round the Sun coincides with the direction in which the Sun rotates round its axis.

Planets. According to mutual position, mass, density, and other parameters, the planets of the Solar System fall into *the inner* (earth-like) and *outer* groups. The basic information on the planets is given in Table 1.

The group of earth-like planets – Mercury, Venus, the Earth, and Mars are relatively small in size and are composed of stone and metallic substance of terrestrial type with high density. They possess an exceptionally inconsiderable mass of atmosphere and are characterized by a relatively low velocity at which they rotate round their axes.

The outer planets comprise Jupiter, Saturn, Uranus, Neptune, and Pluto. They are characterized by huge dimensions, low density of matter, dense atmosphere with the preponderance of hydrogen, helium, and methane, as well as a relatively high velocity of rotation round the axes. Of all the planets Pluto, which only in 1978 was found to have a satellite, has been insufficiently studied. Such giant planets as Jupiter, Saturn, and Uranus are characterized by rings composed of meteorite substance.

FIGURE 1. A structural schematic drawing of the Solar System

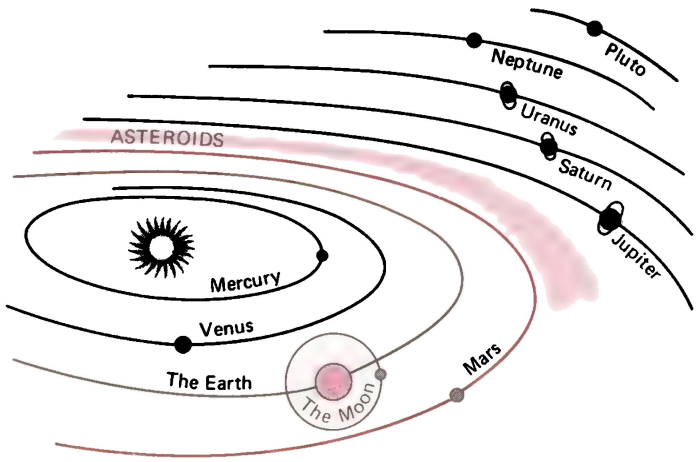


TABLE 1. The Planets of the Solar System and Their Characteristic Features

Planets	Radius (in relation to the Earth's radius)	Volume (in relation to the Earth's volume)	Density, g/cm^3	Mass (in relation to the Earth's mass)	Atmosphere (chemical composition)	Period of rotation round the axis	Period of rotation in orbit (year)	Number of satellites	Distance from the Sun AU*
Mercury	0.37	0.05	5.44	0.06	Ne, He, H_2, Ar, CO_2	58.6 days	0.24	–	0.387
Venus	0.95	0.90	5.24	0.82	CO_2, N_2, Ar, CO, H_2S, H_2O	243 days	0.62	–	0.723
Earth	1.0	1.0	5.52	1.0	N_2, O_2, Ar, H_2O, CO_2	23.94 hs	1.0	1	1.00
Mars	0.53	0.15	3.95	0.11	CO_2, N_2, Ar, O_2, H_2O, CO	24.64 hs	1.88	2	1.524
Jupiter	11.19	1318	1.33	318.0	H_2, He, CH_4, NH_3, C_2H_6	9.94 hs	11.86	16	5.203
Saturn	9.46	755	0.69	95.1	H_2, He, CH_4, NH_3	10.24 hs	29.46	17	9.539
Uranus	3.83	63	1.26	14.6	NH_3, CH_4	24 ± 4 hs	84.01	14 (?)	19.182
Neptune	3.73	58	1.67	17.2	NH_3, CH_4	17.8 hs	164.79	2	30.058
Pluto	0.23	0.01	0.70 ÷ 1.20	0.002 ÷ 0.004	Ne	6.4 days	247.7	1	39.439

AU*–astronomical unit, equal to 149 597 868 ± 0.7 km.

The Earth is a typical inner planet of the Solar System. It is characterized by the presence of properly developed atmosphere, hydrosphere and inner envelopes. Observations from outer space (Fig. 2) have revealed that the Earth is distinguished by the blue colour of its oceans and the greenish and yellow inclusions of continents. The Earth's satellite is *the Moon* (the distance from the Earth is about 384000 km, the period of its rotation is 27 days), the attraction of which causes high and ebb tides in the aqueous and stone envelopes of our planet.

The force with which the Moon influences the Earth is conditioned by inconsiderable distance between them and the commensurability of dimensions (the Moon is 4 times smaller than the Earth). The density is 3.3 g/cm^3, the mass of the Moon is 81 times smaller than that of the Earth. The periods during which the Moon rotates round its own axis and the Earth are the same. That is why one

FIGURE 2. A space photograph of the Earth

of its sides always faces the Earth. The gravity on the Moon is 6 times smaller, which can be accounted for by the absence of any atmosphere.

By its form the Moon represents an almost regular sphere with an inconsiderable bulging (due to gravitational attraction), which faces the Earth. Vast plains (lunar seas) and highland regions (continents) are distinguished in the Moon's relief. The Moon is characterized by proccsses of the disintegration of rocks under the activity of solar radiation (the daily temperature difference amounts to 300°) and meteorite bombardment, as well as magmatic (predominantly volcanic) activity.

The thickness of the Moon's crust is from 30 to 65 km. Its upper part is composed of regolith, or products resulting from the decomposition of original basalts. It is assumed that the lower regions contain the mantle (to the depth of 960 km) and the core.

Asteroids. Between the orbits of Mars and Jupiter, separating the inner planets from the outer ones, there is *a belt of asteroids*, or *small planets.* About 2 000 asteroids have been discovered, but it is supposed that their total number exceeds 100 000, with their general mass being approximately 0.001 of that of the Earth. The largest of them are Ceres (767 km), Pallas (489 km), and Vesta (386 km). The asteroids have an iron and stone composition and have the form of angular blocks.

Meteorites are mineral aggregates of cosmic origin that come into the Earth's atmosphere from the world space. Their smaller varieties (meteors) burn in the atmosphere, while the largest of meteorites reach the surface, and as the result of the shock form explosive funnels which have a shape of a crater. The largest specimen of the latter is the crater Meteor (Arizona, USA). Its diameter is 1.6 km and the depth reaches 150 m. According to Ph. Stacey, the fall of more than 700 meteorites had actually been registered. In two cases (Prshibram in Czechoslovakia and Lost City in the USA), it was possible to photograph the fall of meteorites, which enabled the researchers to calculate their orbits.

According to their composition, meteorites are divided into those of *the iron* variety (siderites), *stony* variety (eucrites), and *the iron and stone* meteorites (chondrites). The first consist of 95% of iron and contain admixtures of nickel and cobalt; there is some reason to suppose that their composition has very much in common with the Earth's core. Eucrites consist of silicates with an admixture of plessite; their composition may well be compared with some of the rocks found in the earth's crust. Chondrites are the ones that are most widely spread (93% of all the finds). On the whole their composition is similar to that of the Earth.

Every year the Earth receives some 16 thousand tons of meteorite matter. The mass of meteorites varies from several grammes to hundred of tons. The largest meteorites that have been found are Goba (Africa) with the mass of 59 t and Cape York (Greenland) weighing 33 t. In the USSR the most prominent meteorites are considered to be Boguslavka (1916) the mass of which is 257 kg, and Sikhote-Alin (1947) with the weight of 130 kg.

Comets are cosmic bodies of elongated form, the composition of which comes very close to the atmosphere of the giant planets. They move along markedly elongated elliptical orbits, approaching the Sun and receding from it beyond the

limits of the Pluto orbit. The comets are not heated bodies, their light is conditioned by the solar radiation. Approximately 1 000 comets have been discovered so far. In those cases when comets deviate from the orbits their collisions with planets and the formation of funnel-like craters become possible. It is assumed that the Tungus meteorite, which fell in Siberia in June 1908, was actually a small comet weighing about 5 mln t that collided with the Earth. Halley's Comet is referred to the so-called periodic comets. The period of its revolution is about 76 years. From 446 B. C. till now it has appeared in the sky 30 times.

The Hypotheses Concerning the Origin of the Solar System and the Earth. Within the whole historical period covering the development of geological concepts the questions pertaining to the origin of the Earth and other planets of the Solar System have always remained pivotal with the scientists. A large number of hypotheses have been put forward. Some of them are discussed below.

In 1755 the German philosopher I. Kant came up with the idea that the origin of the Universe should be interpreted in terms of the primary matter consisting of very small particles. The formation of stars, the Sun and other cosmic bodies was indebted, in his opinion, to the influence of forces of attraction and repulsion in conditions pertinent to the chaotic movement of particles. The French mathematician P. Laplace (1796) associated the formation of the Solar System with the rotatory movement of the rarefied and incandescent gaseous nebula, which led to the emergence of aggregate state of matter, or the embryos of planets. In accordance with the Kant-Laplace hypothesis, the initially incandescent Earth was gradually cooled and compressed, which gave rise to the formation and deformation of the earth's crust. In its time the hypothesis was quite progressive, but with the further development of astronomical studies it proved to be inadequate.

According to O. Schmidt's hypothesis (1943), the planetary system originated from the cluster of cold and meteorite material when the Sun passed through it. The initially cold Earth and other planets became gradually heated under the

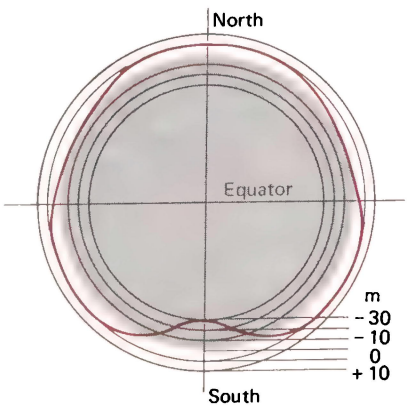
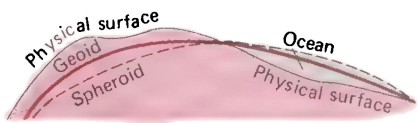


FIGURE 3. The geoid's surface

FIGURE 4. The surfaces of the relief (physical surface), spheroid and geoid

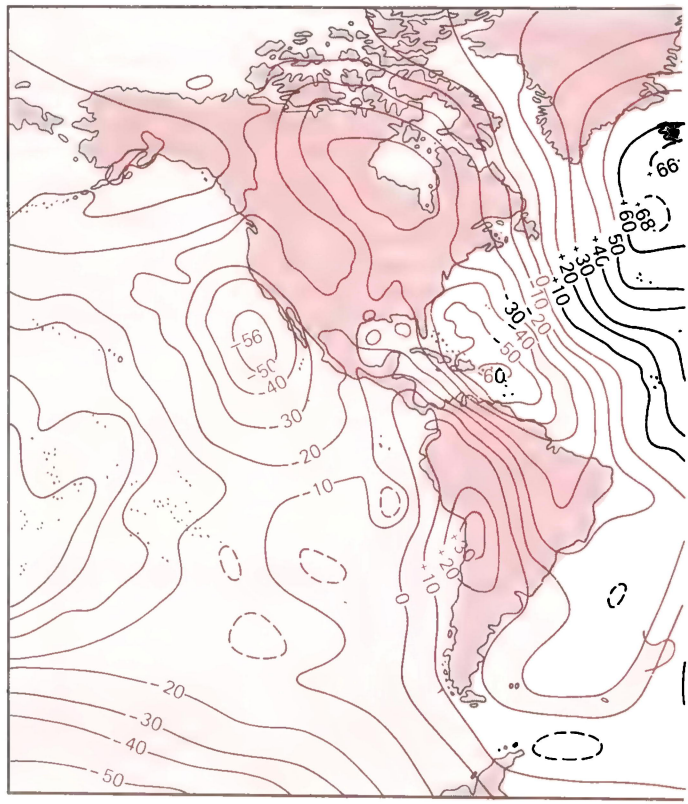


influence of the energy exerted by radioactive decay, gravitational and other processes, followed by cooling. O. Schmidt's hypothesis explained a large number of characteristic features pertinent to the structure of the Solar System, but it lacked any sufficiently convincing arguments with the help of which it would be possible to interpret the controversial problems related to the origin and evolution of the Sun and stars.

In the fifties the Soviet astronomer V. Fesenkov suggested a solution of the problem in terms of the formation of the Sun and the planets from a common source which emerges as a result of the condensation of the gaseous and dust material. Besides, it was assumed that the Sun had originated from the central part of the condensation, while the planets emerged from its outer parts.

Nowadays, the bodies of the Solar System are thought to have been formed from the originally cold cosmic solid and gaseous material by compaction and condensation until the Sun and protoplanets came into being. Asteroids and meteorites are regarded as the initial material of planets belonging to the terrestrial group, while comets and meteors are associated with giant planets.

FIGURE 5. Deviation of the geoid's surface from ellipsoid (in metres)



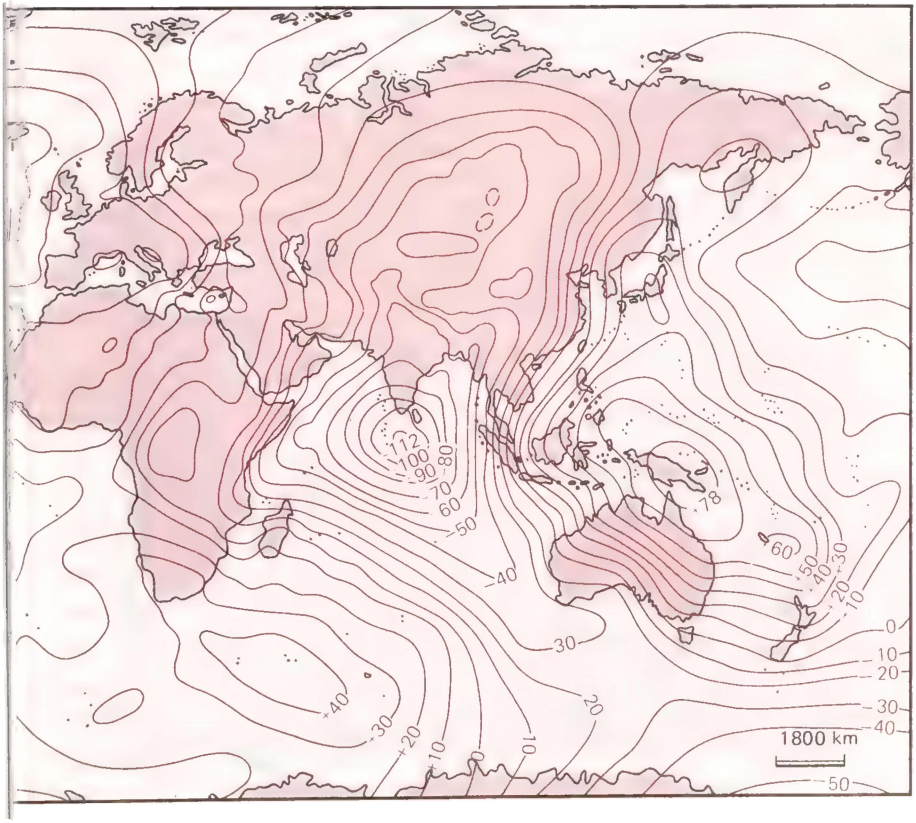
The formation of contemporary enveloping structure of the Earth is regarded against the background of the processes of gravitational differentiation of the initial homogeneous matter.

The Earth's Parameters

The Rotation of the Earth. The character of the Earth's movement in the Solar System influences the amount of solar heat received by various parts of the planet and, consequently, finds its expression in the course of geological processes.

The elliptical orbit of the Earth has a somewhat rounded shape. At the remotest point of the orbit, or *the aphelion*, the Earth is 5 mln km farther from the Sun than at *the perihelion* (the nearest point). This inconsiderable compression of the orbit determines seasonal changes of temperature within the period covering 200 thousand years. *The eccentricity* (value of compression) of orbit changes.

The rate at which the Earth rotates changes during the year and periodically



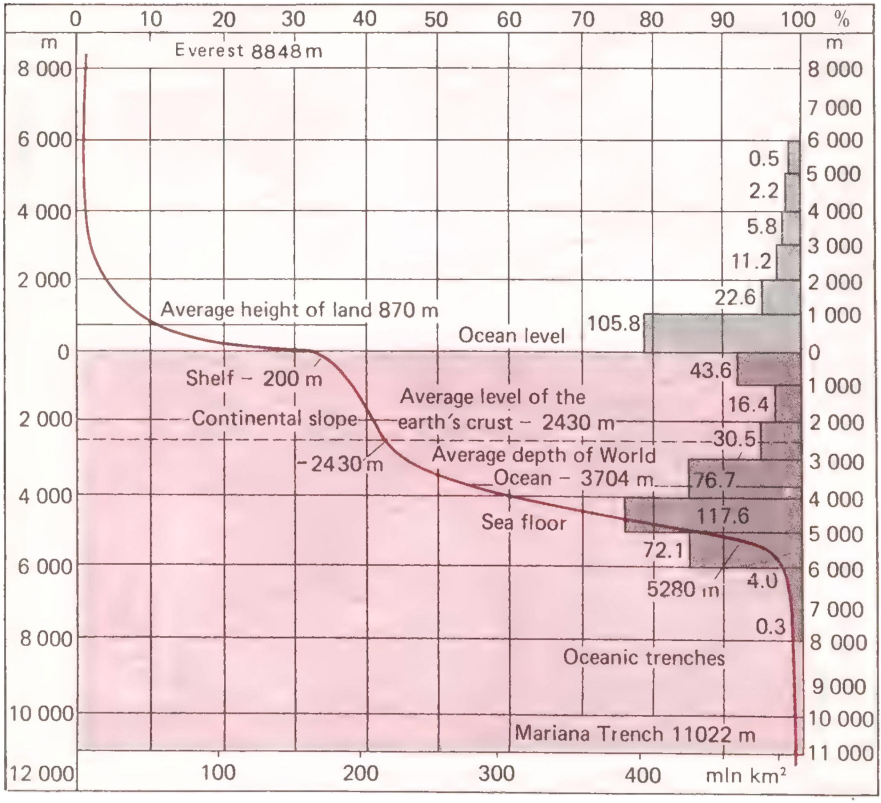
within the cycle of many years. The rotation axis is found to be at an angle of 66°33′, and this slope with the period of 19 years changes too. This vibratory movement of the axis is known as *nutation.*

The Form and Size of the Earth. The configuration or form of the Earth is taken to be the form of its solid body formed by the surface of the continents and the floor of oceans and seas. The form of the planet is determined by its rotation, the relationship between the gravitational and centrifugal forces, the density of the matter and its distribution in the body of the Earth.

Geodetic measurements have shown that a simplified form of the Earth approaches *the ellipsoid of revolution* (*spheroid*). The polar radius (R_p) is equal to 6 356.8 km and the equatorial radius (R_e) is 6 378.2 km. The difference between the radii being 21.4 km, while the value of compression $a = (R_e - R_p)/R_e = 1/298.2$ (F. Krasovsky).

Detailed measurements have revealed that the Earth has a more complicated figure. This figure, typical of the Earth alone, has received the name of *geoid* (I. Lustich). At any point of the geoid the gravitation vector is perpendicular to

FIGURE 6. The Earth's hypsographic curve. Rectangles on the right show high-altitude stages (with surfaces of lithosphere every other kilometre)



its surface, which can be received by the imaginary continuation of the surface of the World Ocean (equipotential surface) under the continents. It is precisely the equipotential surface of the geoid that is taken to be the basic one when the altitudes are estimated in topography, geodetic surveying, and mine surveying (Fig. 3).

Geoid and spheroid do not coincide and the discrepancy between their surfaces reaches $\pm$ 160 m (Fig. 4); on the territory of the USSR, it is $\pm$ 100 m. The determination of the deviations of geoid from spheroid is carried out geometrically and with the help of methods of cosmic measurements (Fig. 5). According to the latest and most exact data it has been established that the Earth has a pear-like form of the cardioidal (i.e., heart-shaped) tri-axial ellipsoid or cardioid. The south pole is situated 242 m closer to the equator than the north pole.

The Earth's mass is $5.977 \cdot 10^{21}$ t, its volume is 1.083 bln km^3, the area covers 510 mln km^2, and the average density reaches 5.517 g/cm^3. The density of its matter increases with depth; the density of the surface rocks is smaller.

The Earth's Surface. The actual surface of the Earth's solid body is characterized by even more complicated configurations than the geoid since its formation is greatly influenced by geological processes.

A greater part, 70.8%, of the surface of our planet is covered with water, the remaining part – 29.2% – is land. The World Ocean is divided by continents into four interconnected oceans: the Pacific, the Atlantic, the Indian, and the Arctic Oceans. The land consists of Eurasian, North-American, South-American, African, Australian, and Antarctic continents and the oceanic islands. The aquatorium of the Pacific Ocean is considerably greater than that of the six continents.

The continents are irregularly distributed on the surface of the Earth. If one were to divide the Earth along the Pacific coast of the continents, it would turn out that it consists of two hemispheres: the continental hemisphere comprising all the continents

FIGURE 7. A sketch-map of the relief of the Atlantic Ocean floor:
1 – shelf; *2* – continental slope; *3* – submarine ridges, rapids and plateau; *4* – plains of oceanic basins; *5* – oceanic trenches

with the Atlantic and the Indian Oceans, and the oceanic one including the Pacific Ocean.

The general regularities in the structure of the Earth's surface are reflected by the schematic hypsographic curve (Fig. 6). The upper part of the curve up to the absolute mark of 0 provides information on the land, the lower part characterizes the relief of the ocean. The highest mark of the land (Mount Everest in the Himalayas) comprises 8 884 m, the lowest mark is 11 022 m (Mariana Trench in the Pacific Ocean). The difference in altitudes makes approximately 20 km.

The average height of continents makes 875 m. The mountainous parts, forming the linear and elongated mountain ridges and belts, are found to be usually correlated with the marginal parts of the continents. Two meridional (East- and West-Pacific) mountain belts and one latitudinal (Mediterranean) belt are singled out. Even parts of the land with the average marks of 200 m are called plains. They occupy nearly 20% of the land's area and are situated in the marginal as well as in the central parts of the continents. The elevated (up to 100 m) hilly parts of land, called the plateaus, cover 53% of its territory.

The average depth of ocean is 3 800 m. The structure of the ocean floor is characterized by the shelf, which goes down to the depth of 200 m (or 5.5% of the earth's surface); *the continental slope*, the depth of which is 3 000 m (34.7% of the surface), *the World Ocean bed* with the depth of 6 000 m, *oceanic depressions* or *trenches*, the depth of which reaches 11 km and more, and *median oceanic ridges* (Fig. 7). As distinct from continents, the ocean is characterized by a symmetrical relief.

Two types of the transition from continents to oceanic basins are distinguished. They are the Atlantic and the Pacific types. *The Pacific type* of articulation is characterized by a marked transition of marginal mountainous structures through the narrow shelf towards the deep-seated oceanic basins. The characteristic features pertinent to *the Atlantic type* of articulation, typical of the coasts of the Atlantic, the Indian and the Arctic Oceans, are distinguished by a gradual submersion of the plain land under the ocean level with the formation of a wide shelf band.

Chapter 2 The Earth's Structure

The Earth, as the most developed planet of the Solar System, is characterized by an envelope structure with the central symmetry. The envelopes of the Earth, or geospheres, are distinguished by their composition, physical properties, the state of the matter, and are subdivided into those that are accessible to direct investigation; and the inner ones, or the ones that are mainly studied by applying indirect methods (geological, geophysical, and geochemical). At present, a close link has been established between the outer and the inner envelopes of the Earth on the one hand and outer space on the other.

Outer Geospheres

The outer spheres of the Earth, viz. the atmosphere, hydrosphere, and biosphere, are parts in the structure of our planet, having their own specific features and playing an important role in the formation and development of the earth's crust. They penetrate into each other and are found to be constantly interacting between themselves and the solid layers of the Earth, which finds its expression in the change of matter and energy.

The Amosphere. It is defined as the gas-like air layer of the Earth, which has the value of $5.15 \cdot 10^{15}$ t or 0.00009% of the Earth's mass. The greater part of the atmosphere (90%) is concentrated within the layer up to the height of 16 km. There is only one millionth part of the air mass above 100 km.

The atmosphere is usually divided into three layers – the troposphere, the stratosphere and the ionosphere (Fig. 8). The intermediate layer above the troposphere is called *the tropopause*, and the layer situated over the stratosphere is referred to as *stratopause*.

The troposphere contains approximately 80% of the whole mass of atmospheric air and has the thickness of 8-12 km over the middle latitudes and up to 17 km above the equator. The air is heated irregularly. The warmest layers are situated in the surface area. With the change in altitude temperature drops to 6 °C every other kilometre, and at the upper boundary drops to − 85 °C.

The stratosphere extends to the height of 50-55 km. The air in the stratosphere is markedly rarefied and is heated directly by the Sun's rays (the temperature differs between − 10 and + 10 °C). Within the confines of the stratosphere we have *the ozone layer*, the thickness of which is 25-30 km, and which absorbs a greater part of the ultraviolet radiation of the Sun that is detrimental to living organisms.

The ionosphere includes three layers: the mesosphere, the thermosphere, and the exosphere. The thickness of *the mesosphere* is 25-30 km; the temperature drops to − 90 °C. In this part of the atmosphere, the so-called silver clouds are formed. In *the thermosphere*, the temperature rises again, and at the height of 400 km it reaches 1 000-2 000 °C. *The exosphere* is characterized by the high temperature of air (about 2 000 °C) and excessively rarefied air. The whole zone of the ionosphere consists of air that is ionized under the influence of ultraviolet radiation and which is capable of conducting current. The upper boundary of the atmosphere is situat-

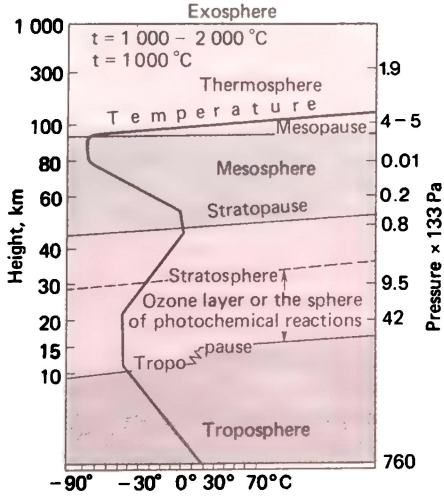


FIGURE 8. The structure of atmosphere

ed at the height of 1 300 km. In the still upper regions its composition becomes very much the same as that of interplanetary space.

The main components of the atmosphere are nitrogen, oxygen, argon, and carbon dioxide which comprise 99.99% of dry air. The minor constituents of the atmosphere include ozone, hydrogen, and inert gases (He, Ne, Kr, and Xe). Particular place in the composition of the Earth's atmosphere is allotted to colloidal particles – dust of various origin: natural, including the cosmic dust, as well as of the anthropogenic type – the industrial smoke, products of atomic explosions, etc. The variable components of air are ozone of radiational origin, as well as SO_2, NO_2, O_2, and NH_3 of industrial origin.

A highly significant part of the atmosphere, as far as its impact on geological processes and objects in general is concerned, is the atmospheric moisture. The evaporation of water from the surface of basins into the atmosphere represents a process of natural distillation. For this reason, the chemical composition of the atmospheric precipitations, as distinct from natural waters, is characterized by marked fluctuations in the content of chloride ion and sulphate ion.

The air masses of the atmosphere are found to be in a constant state of movement under the influence of the irregularly heated surface of the Earth in different latitudes, and the irregular heating of continents and oceans, as well as the Coriolis force. This results in the emergence of periodically blowing winds (breezes, monsoons, trade winds), cyclones and anticyclones, as well as regular air currents. The latter transfer moisture, hard particles (dust), and substantially influence the temperature in different regions of the Earth's surface.

The whole diverse complex of phenomena in the troposphere determines the weather and the climate. *The weather* is the physical state of the atmosphere characterized by wind, temperature, pressure, and humidity. The prevailing state of weather typical of particular physical and geographical conditions is called *the climate*. Depending on humidity and temperature, the following climates are distinguished: *the humid* climate with moderate or high temperature, characteristic of tropical zones and the adjoining regions; *the arid* climate, which is the climate of hot deserts and dry steppes; *the nival* climate is humid and cold and is typical of polar and mountainous regions. Besides, *the temperate and humid*, and *tropical* types are singled out.

The Hydrosphere. The upper boundary of the hydrosphere is determined by the surface levels of open basins. The lower boundary is rather inconsistent, and presumably corresponds to the temperature level of 374 °C, when whole aqueous mass becomes transformed into a gaseous state (critical temperature of water).

Three basic types of natural waters are distinguished in the composition of the hydrosphere. They possess different physical properties and are also different in composition. They are – *the oceanosphere* (the waters of seas and oceans), *the waters of the land and glaciers. The underground waters* occupy an intermediate position and are concentrated in the earth's crust, though they are closely related to the waters of the hydrosphere. The total mass of the hydrosphere comprises $1\,644 \cdot 10^{15}$ t, which does not exceed 0.025% of the whole mass of the Earth. The quantity of oceanic waters is estimated to amount to 1 370 mln km^3 (86.5%), land waters make 0.5 mln km^3, the volume of continental ice approaches 22 mln km^3, and the underground waters occupy 196 mln km^3.

Any kind of waters entering into the Earth's hydrosphere are, to a certain extent, mineralized and can be regarded as natural solutions. As distinct from the atmosphere, the hydrosphere is found to be remarkable for a clear-cut manifestation of *horizontal nonuniformity* (zonality): land waters are basically fresh, while the waters in oceans and seas are saline. The waters of the ocean contain an average of 35 g of salt per one litre (3.5%).The salinity of the World Ocean fluctuates within rather narrow limits – from 3.3 to 3.6%. The relative composition of marine salts is constant, which proves that there exists a stability of dynamic equilibrium between the amount of dissolved substances that enter the ocean from land and their setting.

In the composition of sea water the principal role is attributed to cations Na^+, Mg^{2+}, Ca^{2+}, K^+, and Sr^{2+}, and the anions Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}, Br^-, F^-, and HBO_3^-, which account for the 95.8% of the whole mass of dissolved substances; all the other chemical elements comprise only 4.2%. In addition to ions, the sea water also contains such dissolved natural gases as nitrogen, oxygen, carbon dioxide, hydrogen sulphide, the concentration of which changes with physiogeographical conditions.

The greater part of land waters is formed at the expense of atmospheric precipitations, which are distinguished by a minimal degree of mineralization that is usually retained in glaciers. Continental and sea waters are markedly distinct in the chemical composition of the saline part, since the content of the main ions in them is inversely proportional:

in sea water

$$Na^+ > Mg^{2+} > Ca^{2+};$$
$$Cl^- > SO_4^{2-} > HCO_3^-;$$

in continental water

$$Mg^{2+} < Na^+ < Ca^{2+};$$
$$Cl^- < SO_4^{2-} < HCO_3^-$$

Under the influence of solar radiation, the waters of the Earth's hydrosphere are in a state of constant movement, or *continuous circulation*. Water in the form of vapours of atmospheric moisture, atmospheric precipitation and fluvial runoff, as well as in the form of currents in the oceans covers enormous distances in its flow. When it is in the atmosphere, it is to a maximum degree saturated with free oxygen and then discharges it when in contact with the upper layers of the earth's crust. The process of circulation brings together all the waters of the hydrosphere into a unified system. There also takes place a very close association of natural waters with the atmosphere, the earth's crust and the living organisms of the planet. A special case of biogenic circulation is transpiration the evaporation of water through the leaves of plants (Fig. 9).

In the general circulation of waters on the Earth we can distinguish *atmospheric*, *oceanic*, *lithogenic*, *biogenic*, and *industrial and economic* individual aspects. The latter has the tendency to increase. The moisture of the hydrosphere, together with the substances dissolved in it, takes an active part in the chemical reactions that occur in the hydrosphere, as well as in the interaction with the atmosphere, the earth's crust and the biosphere. Hence, the hydrosphere, just as

the atmosphere, may well be regarded as an active force and the source of exogenic geological processes.

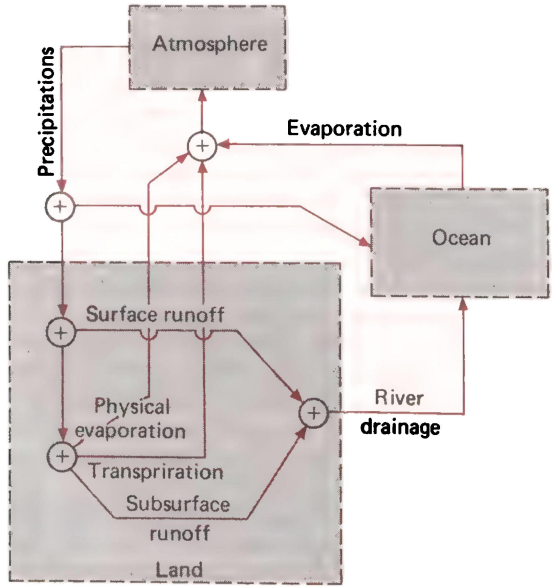
The Biosphere. This layer covers the whole space of the Earth's upper horizons, whence there exists organic life. Contemporary biosphere includes the entire hydrosphere, the upper part of the lithosphere and the lower regions of the atmosphere (below the ozone screen).

The living substance of the Earth with its mass of $2.4 \cdot 10^{12}$ t comprises a practically inconsiderable part as compared with any of the outer envelopes of the planet. But, as far as its active impact on the environment is concerned, its function is preponderant, and it is markedly different in quality from all the other layers.

According to the type of nutrition and their relationship to the environment, the organisms are distinguished as either *autotrophic*, i.e. those that feed on the inorganic mineral substance, or *heterotrophic* – the ones that consume other organisms and their remains. Most of the organisms are *anaerobic*, i.e. those that live in a medium where there is air. A considerably smaller part, predominantly microorganisms, are referred to *anaerobic*, or the ones that live in a medium deprived of oxygen.

What forms the basis of the living substance is carbon, which gives rise to innumerable and various chemical compounds. In addition to carbon, the living nature is remarkable for the abundance of oxygen, hydrogen and nitrogen. The other elements are found in relatively insignificant quantities, though their function in the physiology of organisms can hardly be overestimated.

FIGURE 9. Water circulation (the plus sign designates the summation of flows)



The bulk of the living substance is concentrated in green plants that capture the energy of the Sun's rays and build up complicated compounds of their organisms. This process of the natural structuring of organic substances, or *photosynthesis*, involves into the annual circulation huge masses of the Earth's substance and determines the high oxygen potential of its atmosphere and biosphere in general. Thus, photosynthesis may well be regarded as a regulator of practically all hypergene (surface) geochemical processes, or the factor determining the presence of free energy of the outer layers of the Earth.

In chemical terms photosynthesis is the oxidation-reduction reaction, $CO_2 + H_2O \rightarrow CH_2O + O_2$, as a result of which, at the expense of the absorption of carbon dioxide and water, organic substance is synthesized and free oxygen is emitted.

On a planetary scale in the reactions of photosynthesis the living matter of the biosphere assimilates annually $3.65 \cdot 10^{11}$ t of carbon dioxide and $1.5 \cdot 10^{11}$ t of water, which leads to the formation in the Earth's biosphere of 266 bln t of free oxygen, in addition to which the biomass of the World Ocean remains the principal generator of free oxygen in the atmosphere.

The extinction of organisms involves a process that is contrary to photosynthesis. It is characterized by the decay of the organic substance by means of its oxidation and the formation of decomposition products. Within the confines of the Earth this process is found to be in a state of dynamic equilibrium with photosynthesis, which accounts for the fact that the quantity of biomass on the Earth is constant.

Inner Geospheres

The solid body of the Earth is subdivided into three layers. They are: the central one, or *the core*; the intermediate layer called *the mantle*; and the outer layer known as *the earth's crust*.

Seismic studies* have made it possible to distinguish the surfaces of the discontinuity separating from each other the inner geospheres and heterogeneities within their confines. The discontinuities of the first order are determined by the marked changes in the velocities of the distribution of seismic waves and fix the boundaries between the major layers of the Earth – the crust and the mantle (the Mohorovičić discontinuity), the mantle and the core (the Weichert-Gutenberg discontinuity). The discontinuities of the second order register the inner heterogeneities within the boundaries of the crust, mantle, and core. They correspond to the level on which the variable of seismic velocities changes, i. e. the velocity related to the acceleration of the said velocities with the depth (Fig. 10).

At present there are different views on the inner structure and composition of the Earth (V. Goldschmidt, H. Washington, A. Fersman, A. Ramsay, A. Kapustinsky, and others). The model of the Earth's structure that is recognized as most perfect is the one that is known as *the Gutenberg-Bullen discontinuity* (Table 2, Fig. 11).

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* A more detailed account of seismic studies will be given in Chapter 9.

The core is the inner and the densest layer of the Earth. The sharp variation in the velocity at which longitudinal waves are propagated (from 13.6 to 8.1 km/s), the damping of transverse waves, and the emergence of a high degree of electrical conductivity testify to the changes in the aggregate state of the matter. On the basis of seismic data and the measurement of natural torsional vibrations of the Earth (the absence of any bond between the mantle and the core has been discovered), it is assumed that the outer core is in a state that has very much in common with a liquid. On the border separating the mantle from the core, the temperature presumably reaches 2 500-3 000 °C and the pressure is approximately 300 GPa.

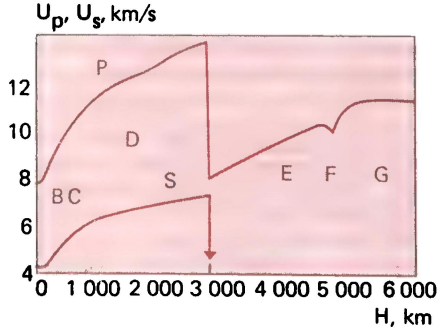
Within the confines of the inner core the velocity of longitudinal waves increases, and the substance remains apparently in a solid state. One can readily assume that at such high values of pressure there occurs the destruction of substance, which, in the inner core, exists in a metallized state or has the form of plasma. The chemical composition of the outer and the inner core is more or less the same (its iron and nickel properties make it very much the same as the composition of iron meteorites). Since Ni and Fe components are predominant here the layer is called 'nife'.

The mantle is the largest intermediate layer of the Earth, which is confined between the Mohorovičić discontinuity (Moho, or M) from above and the Weichert-Gutenberg discontinuity from the bottom. The mass of the mantle comprises approximately two-thirds of the Earth's mass. As far as the substance entering into the composition of the mantle is concerned, only hypothetical assumptions are available.

The upper mantle is characterized by the presence of vertical and horizontal

FIGURE 10. The Jeffrey-Gutenberg seismic model of the Earth:

P – longitudinal seismic waves; *S* transverse seismic waves; *B*, *C*, *D*, *E*, *F*, and *G* – see Fig. 11 and Table 2; the dotted lines represent levels of changes of the derived seismic velocities



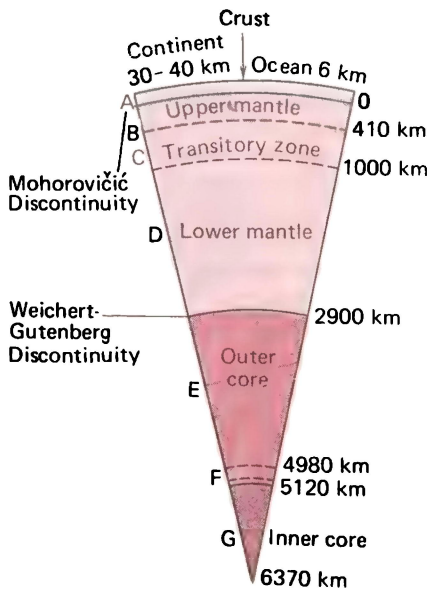


FIGURE 11. The inner structure of the Earth (Gutenberg-Bullen model)

TABLE 2. Layers of the Solid Earth and Their Characteristic Features (The Gutenberg-Bullen Discontinuity)

Geosphere	Depth interval, km	Density interval, g/cm^3	Volume (share of), %	Mass, 10^{25} t	Earth's mass (share of), %	Wave velocity, km/s	
						longitudinal v_P	transversal v_S
Earth's crust (*A*)	0-33	2.7-3.0	1.55	5	0.8	5.5-7.4	3.2-4.3
			Mohorovičić Discontinuity				
Mantle							
Outer mantle (*B*)	33-410	3.32-3.65	16.67	62	10.4	7.9-9.0	4.5-5.0
Transit layer (*C*)	410-1 000	3.65-4.68	21.31	98	16.4	9.0-11.4	5.0-6.4
Lower mantle (*D*)	1 000-2 900	4.68-5.69	44.28	245	41.0	11.4-13.6	5.4-7.3
			Weichert-Gutenberg Discontinuity				
Core							
Outer core (*B*)	2 900-4 980	9.4-11.5	15.16			8.1-10.4	—
Transitory zone (*F*)	4 980-5 120	11.5-12.0	0.28	188	31.4	10.4-9.5	—
Inner core (*G*)	5 120-6 370	12.0-12.3	0.76			11.2-11.3	—

heterogeneities. The composition of this layer under continental and oceanic structures is markedly different. It has been established that at the depth, which in the oceans is nearly 50 km, and on the continents varies from 80 to 120 km, there follows a layer of reduced seismic velocities which is restricted from the upper and the lower regions by a medium of high seismic velocities. In this layer, the elastic wave is propagated in exactly the same way as in a channel, for which reason the layer is called *the seismic wave guide* or *the asthenosphere* (i. e. the geosphere 'lacking in stability'), due to the enhanced degree of plasticity and the softening of the substance entering into its composition. Below the oceans the wave guide is spread to the depth of 300-400 km and under the continents its thickness reaches 100-150 km.

The asthenosphere is correlated with most of the registered centres of intermediate earthquakes. It is assumed that there emerge in it magmatic chambers and that it is the most probable zone where the subcrustal convectional currents are used and where vertical and horizontal movements of the earth's crust are formed i. e. the most important endogenic processes, which are related to the formation of the earth's crust, its deformation, structure, and composition. Hence, the earth's crust with the upper part of the mantle, including the asthenosphere, are often referred to as *the tectonosphere* (V. Beloussov).

According to their seismic characteristic features *the intermediate layer and the lower mantle* are more homogeneous media than the upper mantle. In zone *C* down to the depth of about 600 km we find a rapid increase in the velocity of seismic waves followed by a gradual decrease.

In zone *D* the velocity remains practically constant down to the Weichert-Gutenberg discontinuity.

Indirect data on the chemical composition of the mantle have been received on the basis of the analyses of the deepest magmatic rocks that entered the upper horizons of the Earth owing to the removal of mantle material by powerful tectonic movements.

The calculations made by L. Dmitriev have shown that the average composition of the mantle corresponds to the following relationships of the basic components (mass content, in %): $SiO_2 - 45.5$; $Al_2O_3 - 3.8$; $Fe_2O_3 - 5.3$; $FeO - 3.0$; $TiO_2 - 0.3$; $CaO - 2.1$; $MgO - 42.2$; $Na_2O - 0.4$; $K_2O - 0.1$; $MnO - 0.2$. The composition of the mantle is remarkable for the preponderance of Si and Mg, which accounts for the name 'sima' given to this particular geosphere.

The upper mantle is mainly composed of the iron and magnesian silicates, such as olivine, pyroxenes and garnets, which is in conformity with the peridotite composition of rocks. According to pressure conditions, it is possible to consider that in the transitory layer *C* the basic mineral is olivine in the form of a dense polymorphic modification. Other silicates and aluminosilicates also experience polymorphic transformations and are further decomposed into oxides with a close packing of atoms in the structure. The lower mantle presumably wholly consists of dense varieties, mineral oxides with the predominant value of SiO_2 in the form of a stishovite (the most compact modification of SiO_2).

Geophysical data prove that within the confines of the mantle there is a

preponderance of the solid state of matter, and centres of the melt originate in the asthenosphere. What then is the difference between this condition and the crystalline one, and what accounts for the inconsistent increase in the velocities at which the seismic waves are distributed below the Mohorovičić discontinuity?

On the border separating the earth's crust from the mantle the temperature exceeds 1 000 °C, and the pressure is 2 000 MPa. The assumption is probably true that under these conditions there takes place the transition of the substance from the crystalline state into something like vitreous (amorphic) state. The latter has a higher density than the corresponding substance in a crystalline state.

This state is maintained by high pressure. In the case of a sudden drop in pressure, as, for instance, when the continuity of the earth's crust is disturbed by deep tectonic ruptures, there occurs the melting of the mantle's substance.

The Earth's Crust

The structure of the earth's crust is discussed here as a separate item for the simple reason that geosphere is the main object of geological studies and is by right regarded as a medium of mining industry.

The earth's crust is the upper solid layer of the Earth consisting of magmatic, metamorphic and sedimentary rocks with the thickness from 7 to 70-80 km. It represents the most active layer of the solid Earth – the sphere of activity of magmatic and tectonic processes. The lower boundary of the earth's crust presents, as it were, a mirror reflection of the Earth's surface. Below the continents it goes deep into the mantle, while under the oceans it is very much in common with the Earth's surface.

In geological literature there also exists the term 'lithosphere', which is sometimes erroneously taken to be a synonym for 'the earth's crust'. Lithosphere is the upper rigid shell of the Earth, which includes, in contradistinction to tectonosphere, the earth's crust and the upper mantle and reaches the roof of the asthenosphere. It unites the layers of the planet which are very similar in their properties and aggregate state of matter.

The most important characteristic feature of the structure of the earth's crust is the distinctly expressed heterogeneity, which is manifested in both the vertical and horizontal directions.

The Vertical Heterogeneity. Seismic studies devoted to the structure of the earth's crust have enabled the scientists to single out three layers composed of rocks that have different origin, constituents and structure.

The stratisphere is composed of sedimentary, volcanogenic and sedimentary rocks: clays and clay schists (42%), arenaceous (20%), volcanogenic (19%), and carbonate (19%) rocks. The layer covers practically the whole of the Earth's surface, and in the deep troughs reaches the thickness of 20-25 km (3 km on average). Within the confines of the USSR the sedimentary cover occupies somewhat more than half of the area of continental land and enters into the composition of the surface of the floor of marginal and inland seas. The volume of rocks forming the sedimentary cover exceeds 80 mln km^3 (N. Belyaevsky).

The rocks of sedimentary cover are characterized by poor dislocation, relatively low densities and inconsiderable changes that may well be correlated

with the diagenetic ones. More prominent alterations are connected with the initial stages of regional metamorphism and the lower part of the section and the manifestations of contact metamorphism. The effusive magmatic rocks (mainly traps) have a restricted distribution (Eastern Siberia). The average density of rocks of the whole sedimentary cover on the territory of the Soviet Union comprises 2.45 g/cm^3, the boundaries within which it varies are between 2.28 and 2.80 g/cm^3. The rate at which the elastic oscillations (v_p) are spread in the sedimentary cover is connected with the substance of the rocks, the degree of their compactness and changes from 1.8 to 5.0 km/s and more.

The composition of rocks of which the stratisphere consists proves that their origin can be related to the aqueous medium existing about 3.3 bln years ago. At that time, the atmosphere was much heavier and heated, and presumably resembled the atmosphere typical of Venus today. Hence, the original igneous rocks that composed the Earth's surface were in contact with the hot atmosphere, saturated by vapours of strong acids, and were subjected to intensive decomposition.

The granitic (granitic and gneissic, granitic and metamorphic) layer is called so because of the resemblance that rocks entering into its composition have to the properties of granites. Its constituents include gneisses (37.6%), granodiorites, diorites (19.9%), granites (18.1%), amphibolites (9.8%), crystalline schists (9.0%), as well as gabbro, marble, syenites, etc.

Rocks composing the granitic layer are diverse in their substance and the degree of dislocation. They are represented by invariable, as well as metamorphosed rocks. Depending on the structure and composition the density of the granitic layer changes within the boundaries from 2.6 to 2.8 g/cm^3, thus comprising on average of approximately 2.7 g/cm^3 for the territory of the USSR.

The granitic layer is separated from the sedimentary one by a marked seismic boundary (the sudden change in velocities amounting to 0.7 km/s). The bedded velocity (v_p) in the granitic layer varies from 5.0 to 6.5 km/s with the average value of about 6 km/s. The thickness of the granitic layer on the territory of the USSR makes between 6 and 40 km. There may be a complete lack of the layer in the section. The lower boundary of the granitic layer is known under the name of *Conrad seismic discontinuity*.

The third layer is *the basaltic layer*. It consists of heavier crystalline rocks, which, according to their properties, have very much in common with the terrestrial basalts, or magmatic rocks. The layer is made up of magmatic rocks of various degrees of metamorphism. In some places between the basaltic layer and the mantle there lies the so-called eclogitic layer, where the density is much greater as compared with the rocks of the basaltic layer.

The average density of rocks of the basaltic layer is 2.9 g/cm^3, while the interval within which the density varies is between 2.8 and 3.2 g/cm^3. The rate at which the seismic waves are propagated is found to be within the range of 6-7.6 km/s. Besides, the characteristic features pertinent to the distribution of waves are associated with the type of distribution in the vertical section of the basaltic layer of petrographically heterogeneous complexes.

The average thickness of the basaltic layer within the confines of the continental part of the USSR is approximately 20 km. However, in some regions

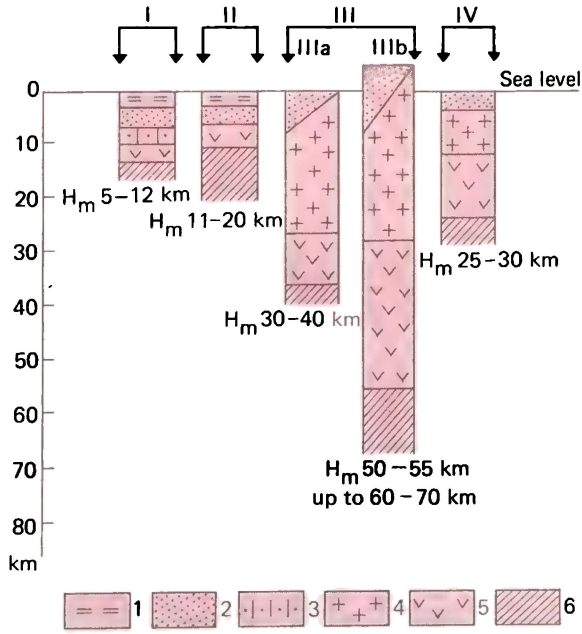
(as, for instance, below the mountain ridges) it can reach 30-40 km. There are regions (the Caspian Sea syneclise, the Dnieper-Donetsk basin and others), where the thickness of the basaltic layer is lowered down to 12-13 and even 5-7 km.

The average thickness of the crust in the continental part of the Soviet Union, according to the data furnished by N. Belyaevsky, is 40.5 km. Some areas are remarkable for a considerable deviation from this average. Thus, the minimum thickness of the crust (7-12 km) is characteristic of oceans, while the maximum thickness (70-80 km and more) is typical of mountainous regions of the continents. The lower boundary of the earth's crust – the Mohorovičić discontinuity, according to the latest data (R. Demenitskaya), in some regions is found to be characterized by interruptions and has the form of several parallel or subparallel boundaries, in addition to which the distinctness and reliability of their contours along the profile tend to alter.

A large number of regularities mentioned above are to a certain extent hypothetical, since the basaltic layer has so far been studied only by means of indirect methods.

Horizontal Heterogeneity. The platform heterogeneity in the structure of the earth's crust is primarily manifested in its structural variety on the continents

FIGURE 12. Schematic sections of the earth's crust:
I – oceanic type; II – suboceanic type – troughs; III – continental type – plains (a) and mountain regions (b); IV – subcontinental type:
1 – water; *2* – sedimentary rocks; *3* – the second layer of the oceanic crust; *4* – granitic layer; *5* – basaltic layer; *6* – mantle (H_m – depth of mantle)



and within the confines of oceanic trenches. This fact was first established on the basis of seismic data by B. Gutenberg. The parts of the earth's crust that are distinguished by the type of geological structure are called *structural elements.*

In terms of the regularities of spatial structure, *oceans* and *continents* belong to the structures of the first (planetary) order, and are markedly distinguishable as far as their geological structure (Fig. 12) and the character of their development are concerned. There is also the crust of a transitory type, viz. *suboceanic* and *subcontinental.*

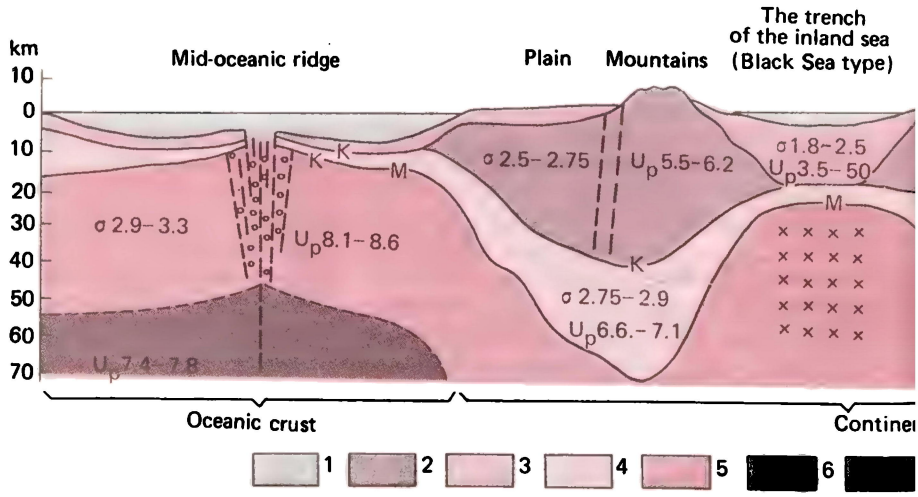
Within the boundaries of structural elements pertaining to the first order, according to the specific features of structure and development, structures of the second order are singled out too: on the continents there are *the platform and geosynclinal* (mountain-folded) *regions*, on the oceanic crust there are *platforms* and *mid-oceanic ridges*. In their turn, the structures that have been mentioned can be subdivided according to the characteristic features of their structure, into smaller structural elements (of higher orders), viz. those that are *global*, *regional*, and *local.*

The minimum thickness of the crust is found on the platforms. The maximum degree is typical of geosynclinal (mountain-folded) regions. An increase in the thickness of the earth's crust in mountainous regions leads to the formation of the so-called 'roots' of the large mountain systems.

Platforms are vast tectonically stable regions. They are characterized by average and consistent values of the thickness of the earth's crust; horizontal or

FIGURE 13. The structure of the earth's crust of continents and oceanic troughs (according to A. Mikhailov):

1 – water; *2* – sedimentary layer; *3* – graphitic and metamorphic layer; *4* – basaltic layer; *5* – the upper mantle; *6* – the mantle with an enhanced degree of density; *7* – the mantle with a lowered degree of density; *8* – asthenosphere; *9* – faults; *10* – volcanic cone; C – Conrad discontinuity; M – Mohorovičić discontinuity; σ – density of rocks, g/cm^3; V_p – velocity of longitudinal seismic waves, km/s



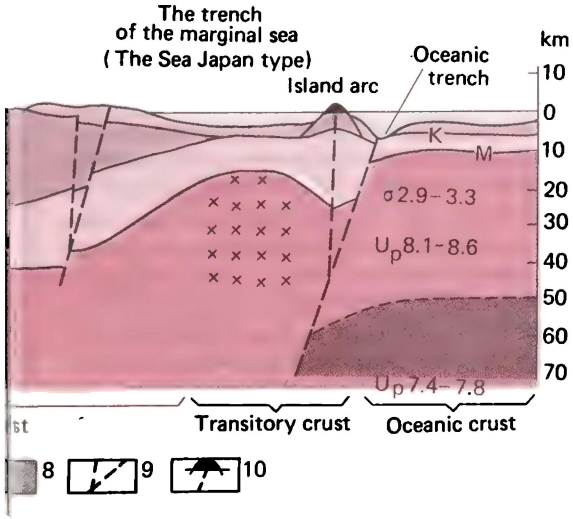
practically horizontal position of sedimentary rocks and plain relief. The platforms have a two-stage structure and consist of more ancient crystalline basement and the sedimentary cover overlapping it (Fig. 13). On the territory of the USSR, there are the East-European (Russian) and the Siberian platforms.

The regions of the platforms with a two-stage structure are referred to simply as *plates*. The outcrops of the basement onto the day surface are called *shields*. Thus, we have the Baltic and the Ukrainian shields on the Russian platform, and Anabar and Aldan shields on the Siberian platform.

Geosynclines are defined as elongated tectonic mobile zones. They are characterized by a considerable (up to 70-80 km) thickness of the earth's crust and its marked changes; dislocated folded and ruptured setting of rocks; and mountainous relief (see Fig. 13). In the geomorphological plan geosynclines are represented by the mountain-folded structures. For instance, the Urals, the Caucasus, the Pamirs, etc.

The crust of the continental type consists of three layers: they are the sedimentary, granitic and basaltic ones. From some parts of the continents the granitic layer is for some reason absent. It is, for instance, eroded in certain regions of the Baltic and Anabar shields, where the basaltic layer is exposed on the surface. According to seismic data, it is not found in some of the deep tectonic depressions. It may well be assumed that in the central part of the Caspian Sea syneclise the sedimentary mass of approximately 18 km in thickness is deposited directly on the basaltic layer.

The oceanic crust differs from the continental variety in that its thickness (6-7 km) is considerably smaller and in composition it lacks the granitic layer. The sedimentary (first) layer has a small thickness under the ocean – in the central part of the ocean floor it is 1-2 km and up to 10-15 km along the periphery (the east coast of the Atlantic Ocean and some regions of the Pacific Ocean). The basaltic layer in oceans has an average thickness of not more than



5-8 km. The tholeiitic basalts (the second layer of the oceanic crust) are concentrated in the upper part, and they are distinguished from the usual basalts by the low content of sodium and potassium oxides. Mainly, in the lower part, the basaltic layer consists of gabbro and amphibolites (the third layer of the ocean crust). The composition of the first two layers are studied by means of deep drilling. The composition of the third layer is known from dredging data. The basaltic layer is found on the rocks of the upper mantle (supraasthenospheric layer) and it is represented by dunites, peridotites and pyroxenites. In places these rocks are uplifted along faults to the level of ocean floors and extracted to the surface by means of dredging.

The suboceanic crust is developed in the inland and marginal seas, where the depth does not exceed 2 km. Its structure, as compared with that of the oceanic crust, is characterized by a greater thickness of loose sediments (up to 3-6 km and more).

The subcontinental crust is typical of the peripheral parts of continents and island arcs. The difference between the subcontinental and continental crusts lies in that the thickness of the former is smaller. The other characteristic feature consists in that the transition from the granitic to the basaltic layer is gradual.

The transition from the continental crust to the basaltic one takes place rather markedly with the depth of the sea approaching 2 km. It is at this depth that the granitic (granitic and metamorphic) layer is tapering out. The basaltic continental layer is discontinued on the continental slope, and is replaced by the oceanic basaltic layer that has its own structure and composition. This type of transition has not yet been given all the attention it deserves.

It is not infrequent that within the zone of the transition from the continents to oceanic basins the earth's crust has a complex block structure. This refers primarily to those regions where on the border with the ocean there are situated young mountain-folded structures (the Pacific coast).

A specific and highly complicated structure of the earth's crust has been found to be typical of mid-oceanic ridges. This is where on the whole the oceanic crust is developed, though there is no clear-cut boundary between the earth's crust and the mantle with the mixing of the substance occurring instead.

The process of matter melting and the separation of planet into layers had the period of 1-1.5 bln years. This period was ended in the interval of 4.5 to 3.9 bln years, where the basaltic layer, covering the whole planet, was formed. It is possible that the separation of basaltic magma was due to the matter differentiation and was accompanied by violent volcanic activity. The period of basaltic layer formation was singled out into the so-called 'lunar' stage of the Earth's development when the vapour atmosphere with temperature more than 100 °C have existed as nowadays it takes place on Venus.

There are three hypotheses of granitic layer formation. The first hypothesis deals with the emergence of granitized crust at the interaction of primary igneous rocks of the basic composition with the vapour atmosphere, chemical weathering, silica concentrations, and subsequent melting of acid magma.

The second hypothesis deals with the emergence of the ancient granite basement of continental masses as 'residual light slag' at the complete melting of primary homogeneous matter of planet.

The third hypothesis deals with the heterogeneity of the accretion of matter that was lasting and two-staged. Heavy elements were mainly developed at the first stage, while light elements (calcium, aluminium with potassium, sodium, and ice admixtures), were mainly developed at the second stage. Later these lithophylic elements of primary granitoids were melted. During the geosynclinal process the growth of granite crust took place when the water medium was available.

Chapter 3 Physical Fields of the Earth

The physical fields created by the planet in general and individual isolated bodies are determined by the totality of properties pertinent to every single physical object. Since there can be no doubt that this connection does exist, it would be natural to disregard the reverse dependence, i. e. on the basis of the study of parameters or elements of various fields of the Earth it is possible to form our judgment of the inner structure of the planet as a whole, its specific features, the structure of different regions, as well as of some regularities in the development of geological processes. It is particularly important to study the geophysical fields when analyzing the physical properties of rocks in specimens and massifs. The study of the properties and the interpretation of data that have been received should be based on the knowledge of the general and local regularities pertaining to the structure of the Earth's physical fields.

Gravitational Field

The Nature and the Characteristic Features of the Gravitational Field. The huge mass of the Earth is what brings about the forces of attraction, which act upon all the bodies and objects that are situated on its surface. The space within which the Earth's forces of attraction are manifested is called *the gravity field*, or *gravitational field*. It reflects the distribution of masses in the depths of the planet and is closely related to the shape of the Earth. Each point on the Earth's surface is characterized by its own gravity: in the centre of Earth gravity is equal to zero.

The value of gravity is expressed in gals (in honour of G. Galilei, who was the first to estimate the acceleration of the free fall): 1 gal = 1 cm/s^2. In practice, however, one thousandth part of one gal or milligal is usually employed. The characteristics of the gravitational field are measured with the help of gravimeters, and less often by means of pendulum instruments. The acceleration of gravity can be estimated by either absolute or relative methods. Those that are widely used are the relative measurements, with which the values at different points are determined in relationship to the point that has a known absolute value.

According to the data obtained from the measurements of gravity, *gravimetric maps* are compiled. The isolines (lines of equal values) on them show the spatial distribution of gravity expressed in milligals. The study of the Earth's gravitational field is the object of *gravimetry* – a branch of science which forms a part of geophysics.

The average value of gravity on the Earth's surface is equal to 979.7 gal. The value of gravity increases accordingly as we move from the equator to the poles – from 978.04 to 983.24 gal. In assuming there to be a homogeneity of masses the theoretical value of gravity can be calculated for each point on the Earth's surface. However, as a result of the irregularity with which masses are distributed in the earth's crust, the estimated value of the acceleration of the free fall differs from the normal (theoretical) one. These deviations of actual values of gravity from those that have been derived theoretically and conditioned by the irregularity in the distribution of masses and other factors are called *gravitational anomalies.*

The gravitational field can be represented as the sum of normal (planetary) field, conditioned by the mass, form and velocities of the rotation of the Earth, and the anomalous field. The anomalities of the forces of gravity are the result of the divergencies in the structure of the actually existing and the ideal Earth.

What may be called a substantial characteristic feature of the Earth's gravitational field is its relative stability within particular intervals of time. Under various geotectonic processes, which lead to the displacement of masses and a partial rebuilding of the Earth structure, there occur changes in the gravitational field. In addition to this, it becomes possible to evaluate the characteristic features of the tectonic processes and their results by the nature, direction and value of changes that are typical of the elements.

The Earth's gravitational field is distinguished by the average levels of intensity (the value and direction of gravity), as well as by the intensity, gradients, areas and contours of the anomalies in the plan and vertical section. The anomalous field is formed by the sum of abnormal fields connected with a variety of geological factors; with the density heterogeneity of the Earth's deep horizons, the depth of setting and the structure of the consolidated earth's crust, with thickness and the specific features pertinent to the structure of the sedimentary cover.

Regional and *local anomalies* of the gravitational field are also singled out. The former are spread over areas covering tens and hundreds of thousands of square kilometres and are distinguished by great degree of intensity (tens of hundreds of milligals). Within the confines of regional anomalies the local varieties become manifested.

The anomalies of the forces of gravity are calculated with corrections for the altitude of observations and the attraction of the layer of masses confined between the equipotential surfaces of the observation point and the surface of geoid. The complete anomalies (the anomalies in free air, or the free-air effect) reflect the differences in the volumes and densities of masses entering into the composition of the lithosphere; the correction is introduced only for the height of the observation point. Bouguet gravity anomalies (the topographic ones) reflect the difference in the densities of these masses, i. e. to a great extent depend on the geological factors proper. Hence, they become widely employed in the geological interpretation of gravimetric data. The correction for free air functions as a component in Bouguet gravity anomaly.

The study of the gravitational field has made it possible to establish a regular bond that exists between the regional Bouguet anomalies with the more

prominent forms of the relief. In addition to this in mountainous regions of the continents it has been found that these anomalies are negative, while above the deep-seated oceanic basins they are positive with the general amplitude reaching 1 000 milligals. The regularities identified in a first approximation are in good conformity with *the hypothesis of the Earth's hydrostatic balance*, or *the principle of isostasy*. However, the latter does not throw light on the manifestation of more minor and practically more significant local anomalies that register the details in the structure of the earth's crust. With a great degree of precision these anomalies reflect the characteristic features of the geological structure of the upper part of the earth's crust and can be used in the exploration and survey of mineral resources.

The Regularities in the Distribution of the Characteristic Features of the Gravitational Field. The character of the gravitational field of the basic structural elements of the earth's crust may well be considered to be established at present. *The gravitational field of the platform regions* with a calm relief is irrespective of the age of the crystalline basement monotypical in its nature. The alternation of inconsiderable in area positive and negative anomalies of intensity, measuring tens of milligals, is registered on the platforms. The anomalies of this type are primarily conditioned by the structure (distribution of masses) of the crystalline basement of the platforms and deeper horizons of the earth's crust, situated at the depth of the first tens of kilometres (Fig. 14).

The gravitational field of mountain-folded regions is distinguished by heterogeneity and the complex structure, depending on the age (stage of geological development). The young Alpine mountainous structures (the Carpathians, the Alps, the Crimea, the Caucasus, etc.) are characterized by the broken relief of the Mohorovičić discontinuity and the changes in the thickness of the earth's crust within the limits of 20-60 km, as well as the preponderance of the basaltic layer, which is clearly marked by positive anomalies. The mountain ridges that were formed upon the ancient foundation (the Urals, the Altai, the Sayan Mountains, the Tien Shan and others), the thickness of whose crust is between 60 and 70 km with the preponderance of the granitic layer, are characterized, as a rule, by negative anomalies.

The littoral zone of the Pacific Ocean is remarkable for marked deviations from the isostasies, which find their expression in the anomalies of the forces of gravity. Besides, the island arcs (Indonesia, Japan, the Kuril Islands and others) are found to be in correlation with the positive anomalies, while the deep-seated trenches are in correspondence to marked negative anomalies. On the whole, the gravitational field of the ocean is exceptionally calm and changes more gradually than on the continents.

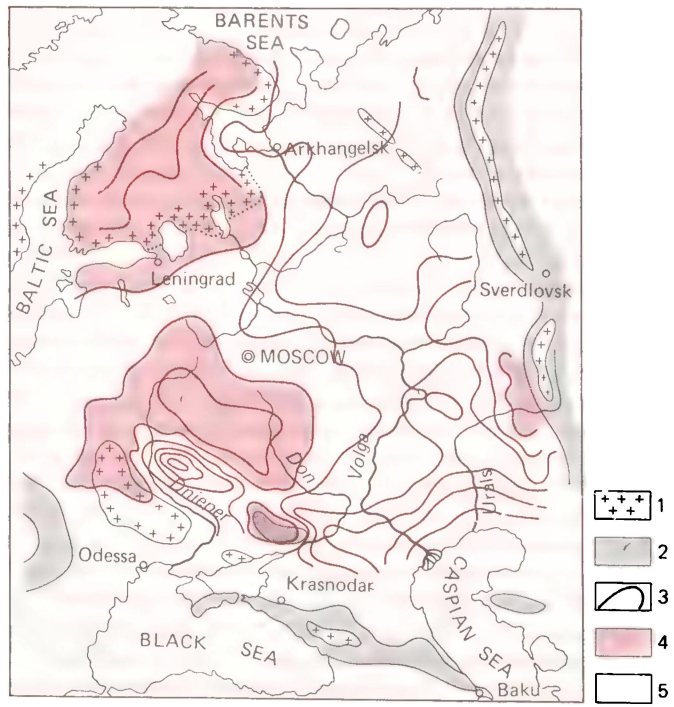
The influence of geological factors on the manifestation of anomalies is regularly decreasing from the abyssal to the surface regions. The heterogeneity of the inner structure of the mantle and the characteristic features of the relief of the Mohorovičić discontinuity bring about the anomalies with the amplitude of up to 1 000 milligals, the more substantial heterogeneities of the inner structure of the consolidated crust (the granitic and basaltic layers) determine the amplitude of anomalies measuring 100 milligals, the more marked fluctuations of the basement relief are accompanied by the anomalies in tens of milligals, while the

specific features related to the structure of the sedimentary cover give rise to the anomalies the intensity of which is estimated in the units of the first tens of milligals.

The anomalies conditioned by the inner heterogeneity of the earth's crust are most typical of the upper part of the consolidated crust that is heterogeneous in its composition and structure, i.e. of the granitic layer, and forms continuous linear systems or mozaic structures of the field of gravity, reflecting the structure of the crystalline complex of rocks of the given region. The intensity of anomalies, connected with the granitic masses or the intrusions of ultrabasic rocks, can reach 30-50 milligals.

The characteristic features pertaining to the structure and composition of the deposits of the sedimentary cover are manifested in regional and local gravitational anomalies. In the horizontal direction, the changes in the gravitational field take place gradually, since they are connected with gradual lithological alterations of rocks within the confines of the region. A more prominent reflection in the gravitational field is the replacements of carbonate or sulphate and carbonate rocks by halite, as well as the marked changes in the

FIGURE 14. A sketch-map of the gravitational field on the East European platform, conditioned by the influence of abyssal factors (according to E. Fotiadi): *1* – outcroppings of Precambrian on the surface; *2* – post-Precambrian folded structures; *3* – isoanomalies; *4*, *5* – regions where the anomalies are spread (*4* – negative anomalies; *5* – positive anomalies)



thickness of the saliferous deposits. Intensive negative anomalies find their expression in the regions where the saline and dome structures are developed (e.g. the North Caspian syneclise). However, the enormous outflows of traps on the platforms do not cause any noticeable anomalies of the field of gravity. These parts of the platform, according to their gravitational characteristics, do not differ from other parts of the platform.

The study of gravitational fields is conducted with the aim of discovering the characteristic features pertinent to the structure of the earth's crust, the singling out of large tectonic dislocations, tectonic zonation of the earth's crust, the establishing of the boundaries of oil-, coal-, and ore-bearing zones and regions, as well as to facilitate the exploration and survey of the deposits of mineral resources (iron, chromites, copper, polymetals, sulphur, mineral salts, etc.).

Terrestrial Heat Field

The Terrestrial Heat Field and Its Nature. The heat conditions of the Earth are extremely complicated, since the planet is in the interaction of two diametrically opposite processes implying the simultaneous absorption and radiation of heat. The heat field is formed at the expense of *the external and internal sources*. The main source of the external energy is *solar radiation.*

The Sun's radiant energy that the Earth's surface receives comprises an average of 8.4 J/(cm^2/min). The world as a whole annually receives approximately $5.44 \cdot 10^{24}$ J of the radiant energy. About 55% of it is absorbed by the atmosphere, the vegetative cover and the soil, and after a number of transformations it is accumulated by the terrestrial plants. The remaining quantity of the energy is reflected into space.

The heat energy of solar radiation sets the air masses of the atmosphere into motion and determines the circulation of water on the Earth's surface. As a result of the incessant movement of air masses and water there establishes *an atmohydrocirculation* in nature, which is the working mechanism of exogenic geological processes. With the help of atmohydrocirculation the solar energy partially transforms into the potential energy of sedimentary rocks, i.e. becomes the Earth's inner energy. The latter is emitted during the process of the metamorphism of sedimentary rocks.

The sources of the Earth's inner heat are: the radioactive decay of elements; the energy of the gravitational differentiation of substance; the residual heat, that has remained since the time the planet was formed; the exothermal effect of polymorphic, electronic, and phasal transitions, as well as chemical reactions; the heat associated with the activity of neutrino; the elastic energy released by earthquakes; the heat conditioned by the processes of tidal friction, etc. At present the values of the Earth's inner heat have been evaluated and it has also been established that the most important of them is the radioactivity of Earth's chemical elements, the main part of which is concentrated in the upper part of the planet. In the course of radioactive decay, the kinetic energy of α-, β-particles, the nucleus loss and the γ-radiation are transformed into thermal energy. According to the data received by various analyses (G. Voitkevich et al), the radioactive generation of heat can comprise $(9.6\text{-}44.5) \cdot 10^{20}$ J per year, which is greater than

the heat the Earth loses (the average of $7.95 \cdot 10^{20}$ J per year). It should be mentioned that in the remote past radioactivity, and consequently the value of radiogenic heat, was much higher than now at the expense of the rapidly extinguishing radioactive isotopes.

Of other inner sources of the Earth's heat mention should also be made of gravitational differentiation and tidal friction. In accordance with the assessment made by V. Beloussov, the former source can render as much heat as is emitted by the radioactive decay of elements. Presumably, the greater part of this heat was dispersed in space, particularly in the initial stages when the planet was formed. The tidal friction can produce the amount of heat approximately equal to 20% of the radiogenic heat.

The Terrestrial Heat Field Structure. According to temperature conditions, the earth's crust is divided into the upper (heliothermal) and lower (geothermal) zones. In the upper zone (up to 30-40 m) the influence of the penetrating into it solar heat is greatly felt. The temperature conditions of the geothermal zone are determined by the subsurface heat. Among the changes in temperature brought about by solar radiation diurnal, seasonal, annual, and age-long ones are distinguished. The greater the period of changes in surface temperatures is, the deeper these changes penetrate into the depths of the Earth. Diurnal changes die down at the depth of about 1.5 m, while the annual ones (their period is 365 times greater) – at the depth of 25-30 m (on the average). This is where the level (zone) of constant temperature is situated. It corresponds to the annual average temperature of the given locality and functions as the boundary separating the upper and lower zones.

The depth at which the belt of constant temperature is situated varies with the latitude of the place and depends on the thermophysical properties of rocks. As the constituent character of the climate rises, this depth is increased too. In the equatorial regions, characterized by inconsiderable changes in temperature, the zone of constant temperature is situated at the depth of 10-12 m, in the mid-geographical latitudes it is 20-30 m (Moscow – 20 m, Paris – 28 m), and in the polar regions the depth measures 40 m.

If the annual average temperature is below 0 °C, then the temperature of the zone will be negative. In this case, the atmospheric precipitations will percolate through the masses of rocks and then turn into ice. It is precisely under these circumstances that *permafrost* is formed. By the latter term we also call the rocks that are deposited at a certain depth from the surface, and that are found to have remained at the negative temperature for many thousands of years and that contain water in the solid state. The upper layer is called active; it melts only during the summer period at the depth from several centimetres to 3.5 m. Then comes the mass of frozen rocks, with the melting rocks below them.

Permafrost is widely spread on the surface of the Earth and occupies approximately 25% of its area (Fig. 15). In the USSR the permafrost zone is spread over 45% of its territory. The whole region within which permafrost is developed is divided into the zones where the permafrost is complete (the temperature is between -2 and -11 °C, the thickness of the permafrost layer being 700 m northwards, and 60-120 m in the south); the talik permafrost (with the temperature from 0 to – 5 °C, the thickness between 10 and 150 m); and the

island permafrost (the area of permafrost rocks in the zone is less than 50%).

The character pertinent to the conditions in which the geological processes take place, the conditions of underground waters and the engineering and geological conditions within the permafrost zone are markedly different from what they are outside it. All this determines the specific character of those conditions in which the economic development of the territory within the permafrost zone takes place.

The Heat Conditions of the Earth's Crust. Below the zone of constant temperature we find a progressive heating of the deeper regions of the earth's crust that immediately depends on the heat flow. The latter is determined as the product of the temperature, or geothermal gradient and the heat conduction of rocks. By geothermal gradient we mean a value expressed in °C/m, which characterizes the increase in temperature of rocks as the depth becomes greater. The geothermal gradients of various regions of the Earth are considerably different from each other and vary within the limits from 0.1 to 0.01 °C/m. The reverse value, or the geothermal gradient, changes between 10 and 100 m/°C. Deviations from the values of geothermal gradient are found to be conditioned by the following factors:

various heat conduction of rocks, with the rise in which the geothermal gradient is diminished;

conditions of bedding: the geothermal gradient is maximum in the case of horizontal bedding and minimum when the bedding is vertical, since the heat conduction of rocks is maximum along and minimum across lamination; in those instances when the bedding of rocks is inclined and they have different degrees of heat conduction, the geothermal gradient can rapidly change within a short distance;

the temperature and the conditions of the circulation of underground waters: the hot springs rising from very deep regions sharply diminish the geothermal gradient;

the relief of the territory: as the relief becomes more intersected, the geothermal gradient grows;

the remoteness from oceans and seas: all other conditions being equal, the geothermal gradient is lower on the coast, which is conditioned by the cooling effect of water basins;

geochemical factors: in those regions where geological bodies are spread (oil, gas and coal deposits), and where intensive oxidizing exothermal reactions take place, the geothermal gradient is characterized by a positive value;

the volcanic activity: in the regions of recent volcanic activity owing to the influence of the volcanic foci situated at an inconsiderable depth the geothermal gradient can have a low value (for instance, 1.5 m in the region of Pyatigorsk).

It is also necessary to make a special note of the fact that the value of geothermal gradient is different not only in different parts of the surface of the earth's crust, but also at various depths of one and the same region, i.e. rate at which temperature changes with the depth may well be regarded as a variable value.

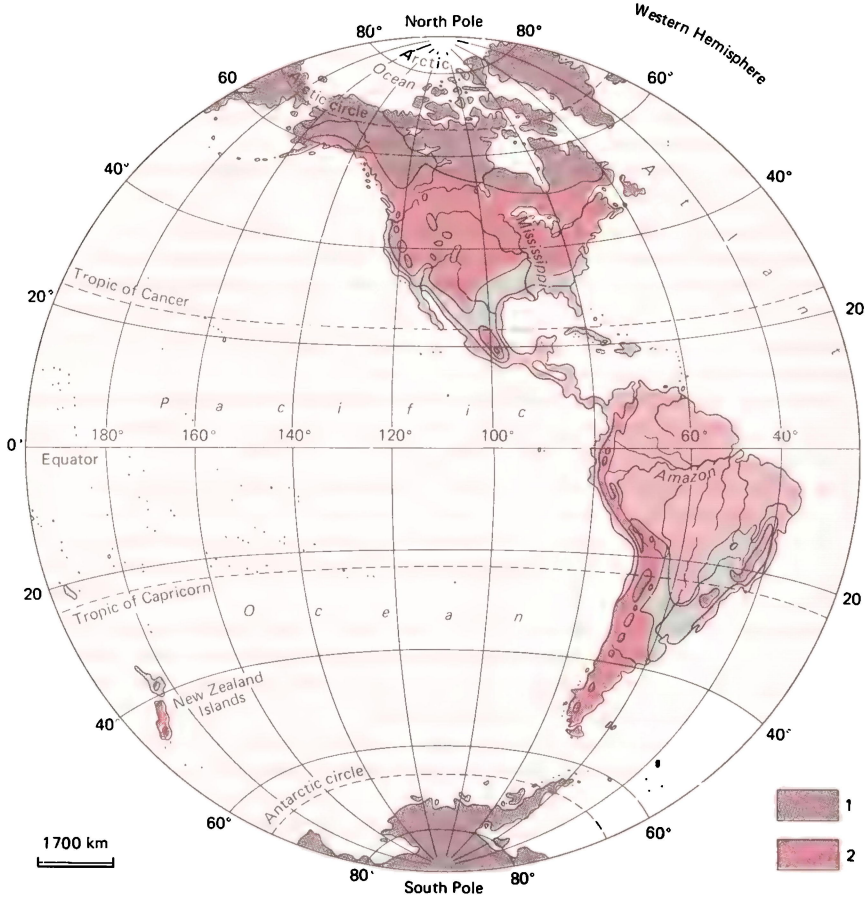
The density of the heat flow for the whole of the earth's crust is taken to be $6.03 \cdot 10^{-6}$ J/(cm^2·s) with the changes almost from 0 to 58 J/(cm^2·s). The

changes are correlated with the contemporary endogenic zones, as well as with the degree to which the asthenosphere is defined. On the whole, the heat flows registered on continents and in oceans are closely related to each other. However, on the individual parts of structural elements of the first order there establish anomalies of the heat flow, or values that markedly deviate from the mean values of the flow for the given region.

On the continents and within the confines of ancient crystalline shields, where the asthenosphere is either absent or is poorly expressed, the average density of

FIGURE 15. The Earth's cryogenic regions:

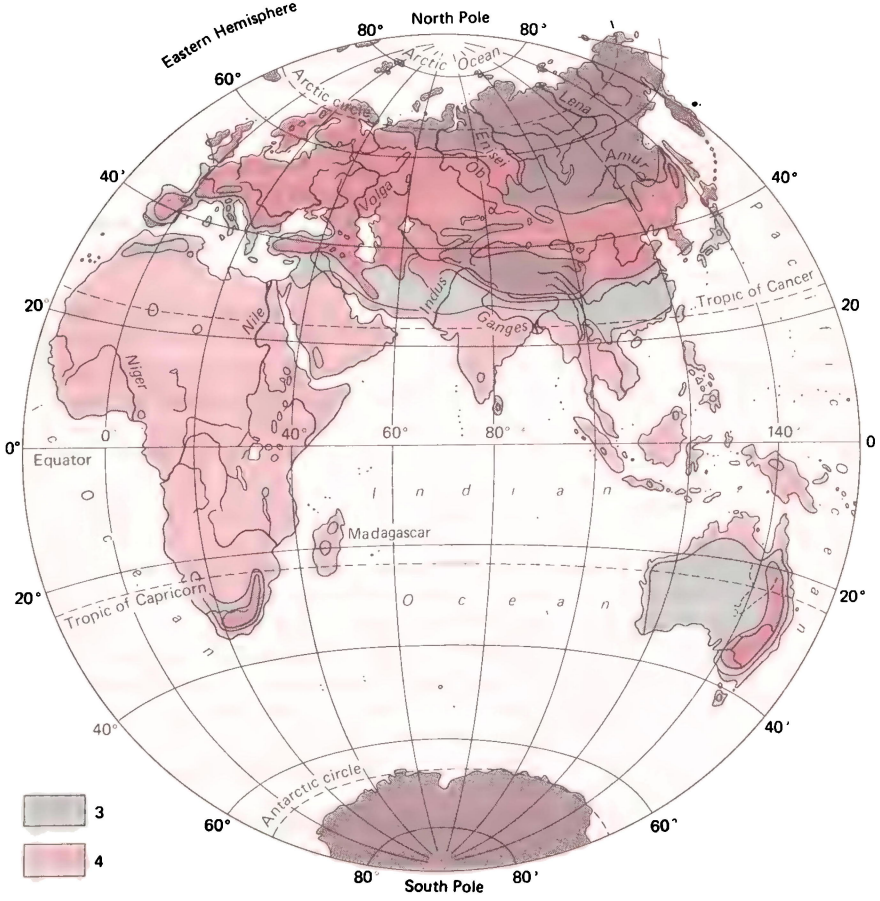
1 – the region of perennially frozen rocks and ice sheets; *2* - the zone of regular seasonal freezing of soil; *3* – the zone of temporary and irregular freezing of soil; *4* – the regions where the soil does not freeze



the heat flow is equal to 3.76 J/(cm^2·s), while on the platforms it is 4.60.*

In the zones of weak orogenesis at the place of Paleozoic geosynclines (the Urals and Altai), the intensity of the flow rises to 6.27, while in the regions of tectonic activization, where the asthenosphere is properly expressed, it is 7.52. The intensity of the flow is still higher in the rift zones (about 8.36). The highest heat flows (nearly 15.0) on the continents are discovered in the regions of contemporaneous volcanism, where the asthenosphere rises right up to the sole of the earth's crust.

On the continents the most obvious anomaly is Hungary, where high values of the heat flow were found everywhere. Its mean value here comprises approximately 12.7, which is considerably higher than what we have in Canada, Australia, Japan, and England. This geothermal anomaly represents an isolated



* For brevity here and further only numerical values of flow density without dimensions, e. g. 4.60, 6.27, 7.52, are given.

region of enhanced heat as compared with the surrounding areas of Central and Eastern Europe.

In oceans a close link is established between the high heat flows and the middle ridges. Places have been found where the value of the flow is greater than 30, while the average values do not exceed 8.4. The farther we go from the crest of the medial ridge, the more rapidly the heat flow drops to 4.6-4.8. The graphical representation of heat flows approximately repeats the relief characteristic of the ocean floor.

The terrestrial heat field is characterized by a considerable variety of values of the flow, and considerable local heterogeneities with marked oscillations (up to 100%) within short distances.

The Temperature in the Depths of the Earth. At present we know very little about the temperature conditions in the Earth's depths. The basic information on the temperature conditions have been received as a result of direct geothermal measurements in mining works and boreholes, the data on the generation of heat by the main types of rocks, and the temperatures of outflowing lavas as well as information on electric conductivity.

For instance, the direct measurements of the temperature of crystalline rocks that were conducted in the Kola Peninsula borehole provided the following values (in °C): at the depth of 7 km – 120 °C; at the depth of 10 km – 180 °C; at the depth of 12 km – more than 200 °C. In 'Bertha Rodgers' borehole (the USA), which was drilled in the sedimentary cover, the temperature at the depth of 9.5 km reached 243 °C.

It is considered that the geothermal gradient is preserved at the depth of 20 km. Below this level the temperature rise is retarded. According to the calculations made by V. Magnitsky, the change in temperature with the depth under the continents and oceans takes place in the following way:

	Continent				Ocean	
Depth, km	20	40	50	11	40	50
Temperature, °C	380	650	700	130	850	1100

At the depth of 100 km, the temperature, presumably, reaches 1 300 °C (similar temperatures are found with lavas erupted by the volcanoes the foci of which are situated at these depths). At the depth of 400 km, the temperature is equal to 1 700 °C, at 2 900 km it is 3 500 °C, and at 5 000 km the temperature rises to 5 000 °C. It is assumed that the temperature is the same in the inner core as well as in the outer core or slightly higher. The *A* and *B* layers come into the stage of cooling while the *C* and *D* layers and the core are still heated owing to radioactive decay of unstable infusible heavy elements shifting to the centre of planet.

The Practical Application of the Earth's Heat. The development of Soviet and world economy is based on the rapidly growing consumption of fuel and energy resources. In the twentieth century the population has increased 2.2. times, while the consumption of energy has become 8.5 times greater. There is every reason to suppose that by the end of the century the consumption of energy will be 20-25 times more than what it is today. Under these circumstances thermal energy

confined in the depths of the Earth is competitive with traditional sources of energy (coal, oil, gas, and nuclear fuel).

The general geothermal resources correspond to the amount of heat energy accumulated by the lithosphere to the depth, technically accessible with the aid of modern means of drilling (about 10 km). According to their physical parameters the distribution and technological conditions of recovery of geothermal resources are conditionally divided into *hydrothermal* (natural vapour, vapour and aqueous mixtures, and thermal waters) and *petrogeothermal* (the thermal content of rocks). The technology of developing geothermal deposits is a relatively simple process as far as its technology is concerned; it implies the drilling of boreholes and the extraction of natural (thermal waters) or artificially uplifted heat-transfer agent.

The study of the terrestrial heat field is also necessary for the prognostication of those conditions that are pertinent to the underground development of coal and ore deposits. Nowadays the recovery of mineral resources is already conducted at depths of 1 500-4 000 m and there is a tendency to increase these depths. In this connection what acquires current importance is the organization of such conditions that would facilitate the labour process itself.

Lastly, the heat conditions of the mineral resources may well be regarded as an indicator of deposits of combustible mineral resources and sulphide ores. Therefore, the parameters of the anomalous heat field are employed in operations involving exploration and survey.

Magnetic Field

The Nature, Structure, and the Characteristic Feature of the Magnetic Field. Round the world and within it there exists a magnetic field. According to the data of space research, it extends beyond the confines of the planet over a distance ten times exceeding the Earth's radius, thus forming *the magnetosphere* (Fig. 16). A complex asymmetrical external form of the magnetosphere, continually changing its configuration and force, has been established. From the side of the Earth, lit by the Sun, the magnetosphere is considerably compressed, while from the opposite side it is elongated with the formation of a magnetic sheath.

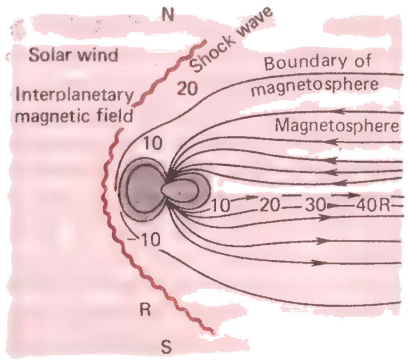


FIGURE 16. **The structure of the earth's magnetic field (striation shows radiation belts)**

The asymmetry of the magnetosphere is conditioned by the influence of solar wind (a flow of cosmic radiation). At the distance of ten earth's radii (R) along the Earth and the Sun line, the regular magnetic field is transformed into an irregular one, or a chaotic field, the boundary between which is called a magnetic pause (the boundary is stable as regards the flow of solar wind). The chaotic magnetic field is then transformed (at the distance of 14 Earth's radii along the Earth and the Sun line) into an undisturbed interplanetary field. The magnetic field intensity of the Earth undergoes changes inversely proportional to the cubic distance from the Earth.

The form of the contemporary magnetic field of the Earth is very much the same as the one that was created by the magnetic dipole placed into the nucleus at a distance of 436 km from the Earth's centre. This dipole is slightly (11.5°) inclined to the axis of the Earth's rotation and hence the magnetic poles are situated close to the rotation poles. The south magnetic pole is located in North Greenland near the Thule observatory (74° S and 100° W), while the north magnetic pole is in the north-eastern extremity of Victoria Land in Antarctica (68° S and 145° W).

The confined (from one pole to the other) character of lines of force of the dipole geomagnetic field leads to the formation of the system of magnetic traps for the charged particles that are formed in the upper parts of the atmosphere under the influence of the Sun. Thus, there emerged *the zones of cosmic radiation*, or *Van-Allen zones* that surround the Earth and are filled with the ions of atmospheric gases and elementary particles.

The Earth's magnetic field that can be observed markedly differs from the dipole field in that it is superimposed by the external and non-dipole field. The external field is connected with the movement of electric charges in the ionosphere and its intensity is low. The non-dipole field consists of irregularly distributed parts of high and low intensity, which are displaced on the Earth's surface westwards at the speed of 0.5° of geographical longitude per year. The unstable position of the magnetic poles is determined by the impact of the heterogeneous, rapidly changing non-dipole field; on the magnetic poles the non-dipole horizontal constituent completely destroys the horizontal constituent of the dipole field. The position of the magnetic field varies relatively fast, in correlation with the alterations in the non-dipole constituent.

According to the prevailing modern concepts, the geomagnetic field is associated with the complicated loop-like movements of the electrically charged particles within the liquid outer core of the Earth, which is regarded as a self-exciting hydrodynamic machine, acting under the joint influence of the Earth's rotation and heating, causing the convection of the material.

The rapid change of the non-dipole constituent or component is accounted for as a result of the vortex movements of the liquid at the boundaries of the nucleus and the mantle, and its displacement in the westward direction is conditioned by a smaller angular velocity of the outer zone of the nucleus as compared with the mantle.

The Earth's magnetic field influences the orientation of ferromagnetic minerals (magnetite, ilmenite, titanomagnetite, hematite, and pyrrhotite) in rocks. This influence is manifested, when the hard ferromagnetic minerals swim

in a melt during the solidification of igneous rocks, or in a solution in the course of the formation of sedimentary rocks. What reacts most markedly to the Earth's magnetic field are the ultrabasic and basic igneous rocks (basalts, gabbro, peridotites, and serpentinites) and red-coloured continental sands of the sedimentary origin. Guided by research into the orientation of ferromagnetic minerals (but only in completely unaltered and non-dislocated rocks), it is possible to determine the direction of the magnetic field within the period of formation of the corresponding rock. These investigations of *paleomagnetism*, i.e. of 'fossil' magnetization of rocks, has acquired at present great significance.

Paleomagnetic observations have established that in the course of the geological history there occurred inversions (the transformation of the magnetic field from the positive variety into the negative one and conversely so), and the dislocation of magnetic poles. The recent inversions have been studied best. The contemporary positive epoch which began 0.7 mln years ago was preceded by the negative epoch covering 1.7 mln years, which came in place of the positive epoch (0.9 mln years) and the earlier negative epoch (1.2 mln years). Inversions have also been established for more ancient periods of the geological time.

Dislocations of magnetic poles, i.e. the turns of the Earth's magnetic axis, are found to have been typical of the whole Phanerozoic (Paleozoic, Mesozoic, Cenozoic) period. The periods of the rapid dislocation of poles are correlated with the periods of frequent inversions of the magnetic field.

In accordance with the theory, the Earth's axis of rotation and the mean axis of the magnetic field coincide. Hence, the dislocation of the magnetic poles presumably means a turn in space of the globe in general or its outer layers in respect of the axis of rotation. This leads to a highly important conclusion in geology, that the dislocation of magnetic poles takes place at the same time as the dislocation of geographical poles, with which the dislocation of all climatic zones is correlated.

The basic characteristics of geomagnetic field are its declination, dip and tension.

Magnetic declination is the angle between the axis of the magnetic needle (the magnetic meridian) and the geographical meridian. The lines connecting the points with the same values of magnetic declination are called *isogonic lines*, or *isogons*. The latter when characterized by zero declination are referred to as the *agonic curve*. It divides the Earth's surface into two parts: the region covering the Atlantic and the Indian oceans, Africa, and a considerable part of Europe are with the western declination. The remaining part of the Earth's surface is with the eastern declination. In Moscow the declination is 7° to the east.

The term *magnetic dip* is applied to slope of magnetic needle to the horizon. Northern and southern varieties of inclination are distinguished. Its value varies between 0 and 90°. The lines connecting points with the same values of magnetic dip are known as *isoclines*. Their zero variety is called *magnetic equator*.

The force of the Earth's magnetic field is expressed by a vectorial value, or *magnetic* strength. The unit measuring magnetic strength is one hundred-thousandth part of oersted, called gamma (γ). The lines joining the points of magnetic strength that have the same values are called *isodynamic lines*.

Magnetic strength increases from the equator to the magnetic poles. Near the geographical equator there passes the line of minimal magnetic strength, or the dynamic (*magnetic*) *equator*.

The structure of the magnetic field is studied by means of constructing maps of various values of magnetic declination, magnetic dip, and magnetic strength. Maps are accordingly made of isogonic, isoclinal, and isodynamic lines.

The structural changes of the geomagnetic field discussed above – inversion and dislocation of magnetic poles – refer to periodic variations. In addition to them, there exist non-periodic variations, or intensive changes entering into the composition of the magnetic field and conditioned by the outbursts of solar activity. These non-periodic variations of the field are often accompanied by Northern Lights, the weakening or cessation of short-wave radio communication, and are called *magnetic storms*. The latter can be regarded as precursors of earthquakes, since it is not seldom that seismic shocks are preceded by a marked excitation of the magnetic field.

The Magnetic Field of the Structural Elements of the Earth's Crust and Its Anomalies. It is customary to consider that the magnetic field observed at some point of the Earth (H_p) is the sum of the field of uniform magnetization of the Earth (H_0 – the field of the Earth's dipole), world or continental (H_c), regional (H_r) and local (H_l) anomalies, as well as the additional field (H_a), connected with the external factors.

The sources of the field H_0 are situated on the border with the nucleus. Most probably the field H_c is also associated with the abyssal factors, and, therefore, the sum $H_0 + H_c$ is taken to be the Earth's normal field. The anomalies H_r and H_l are related to the characteristic features pertaining to the distribution of rocks distinguished by their magnetic properties in the lithosphere.

The anomalous field of continents clearly manifests the specific features of their geological structure: what is easily distinguished includes platform regions, shields, and geosynclines. Its main characteristic feature is disbalance, variegation, marked distinction of adjacent parts and sometimes uniformity in the areas of different geological structure.

The shelf regions of the ocean are characteristic of a complexly constructed magnetic field with a great variety of extensions, configurations and intensities of anomalies. As far as their appearance is concerned, the magnetic fields of the shelf look very much like the fields of platform regions.

The magnetic field of oceans is characterized by a regular, harmonic, fibrous, and ordered structure. Besides, the magnetic field of the mid-oceanic ridges has a surprisingly similar structure in different oceans of the world. These fields are uniform in intensity, and the orientation of anomalies is maintained rectilinear over great distances.

The floor of oceans is remarkable for *banded magnetic anomalies* (Fig. 17). They are extended linearly for hundreds of kilometres and are parallel to mid-oceanic ridges. In magnetic profiles we find a gradual increase in the intensity of anomalies as they approach the axial line of ridges. From the crest to the slopes the magnetic anomalies become rapidly slackened. English geophysicists F. Wine and D. Matthews (1963) discovered that the anomalies of equal intensity, form and width are situated symmetrically in respect of the central

band, which corresponds to the rift valley. The general width of alternating positive and negative bands comprises approximately 35 km.

According to their magnetic properties rocks are considerably distinguished and can be divided into highly-magnetic, weakly-magnetic, and those that are practically non-magnetic. As a rule, a decrease in the basicity of rocks is accompanied by weakening of their magnetic properties, which, in accordance with this feature, can be brought together in the following series: ultrabasic, basic, median, and acid magmatic formations, terrigenous, organogenic, and hydrochemical sedimentary rocks. Since the rocks with enhanced magnetic properties usually form isolated bodies and beds among the weakly-magnetic rocks, the morphology of their distinction determines the structure and form of magnetic anomalies.

Regional and local magnetic anomalies are distinguished from each other by their orders, intensity, gradients, areas, extension, contours in the plan, and the vertical section.

The intensity of anomalies varies from the first hundreds to several thousand gammas; there is a predominance of anomalies with the intensity of about 1 000 gammas. Anomalies can have clear-cut boundaries in the plan, or, merging with each other, can form complex anomalous contours. According to their form anomalies are distinguished as linear, isometrical, and irregular (complex). The extension of isolated anomalies comprise units – hundreds of kilometres; while the width is measured in units – tens of kilometres.

The upper boundary (edge) of magnetic masses is situated at different depths – from day surface to the depth of 10-15 km and below; the lower edges of magnetic masses on continents seldom go below 15-20 km, i. e. do not go beyond the confines of the granitic layer. In oceans the magnetoactive masses can be found in the upper mantle. And lower edges of magnetic bodies reach maximum depths in zones of deep faults, which are correlated with the intensive banded magnetic anomalies. It has recently been established that there is the presence of magnetoactive masses in the sedimentary cover, conditioned by postorogenic (platform) magmatic processes. If for the East European platform the anomaly-forming importance of magmatic bodies confined in the cover is secondary, then for West-Siberian and East-Siberian platforms its significance can hardly be overestimated.

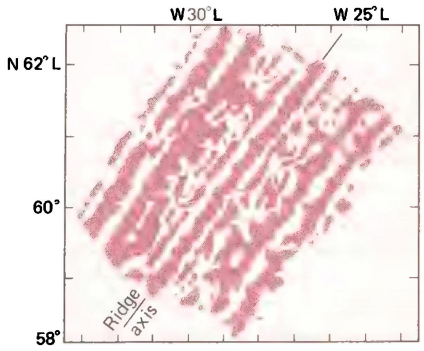


FIGURE 17. Banded magnetic anomalies above the rift of the mid-Atlantic ridge (Reykjanes, Iceland)

The largest local magnetic anomalies in the world include the Kursk anomaly, conditioned by a relatively not deep position of ferruginous quartzites. Here the values of magnetic declination varies from 0 to 180°, while those of dip varies between 40 and 90°.

The study of anomalous magnetic field which is received as a result of aeromagnetic, hydromagnetic, and land surveys is at present widely employed for the research into the structure of the earth's crust, and for the exploration and survey of various mineral resources.

What is closely related to the Earth's magnetism is its *natural electric (telluric) field*, which of all the physical fields of the planet has been less studied. Today we have too little information on the structure and temporary variations of the electric field. The external and internal factors conditioning the electric field have not been established with a sufficient degree of reliability.

It is assumed (T. Rikitake) that in addition to artificial disruptions practically all fluctuations of telluric currents are brought about by electromagnetic induction within the Earth at the expense of the changes in time of the external magnetic field. Factors causing telluric currents also include: stratospheric and electric processes (oscillations of ionosphere and Northern Lights); boundary and electric processes (filtration and electrical processes, convection currents in the lower layers of the atmosphere, thunderstorm processes, etc.); lithospheric and electric processes (rising of contact tensions, thermoelectric and electrochemical processes); geomagnetic variations, caused by oceanic tidal currents; connected with earthquakes; with volcanic activity; and deep thermodynamic processes.

At present, based on the Earth's natural electric field, geophysical methods have been developed for studying the inner structure of the earth's crust, and for the prospecting of deposits of mineral resources.

II The Earth's Crust (Composition and Age)

The Earth's crust seems to be not an inert mass but the mass of matter that is permeated by active energy.

V. VERNADSKY

Chapter 4 Chemical Composition of the Earth's Crust

The earth's crust consists of rocks of different composition and origin. Any rock represents a natural paragenetic association of minerals. The latter, in their turn, are chemical elements or their natural compounds. Hence, in the order of increasing the complexity of its organization, the substance of the earth's crust forms the following consecutive series: chemical element – mineral – rock – complex (formation) of rocks.

The problems pertaining to the composition of the earth's crust, the regularities of its changes in space and time lie within the domain of *geochemistry*, the science that is still regarded as relatively young. According to the data of contemporary geochemistry, 93 chemical elements have been discovered in the earth's crust (97 in outer space).

Most of them are complex, i. e. they are represented by the mixture of various isotopes. The earth's crust is known to contain more than 360 isotopes. Only 22 chemical elements, e. g. sodium, fluorine, phosphorus, manganese, and gold do not have isotopes and are accordingly called simple.

Distribution of Chemical Elements in the Earth's Crust

The problem concerning the distribution of chemical elements in the earth's crust belongs to the number of basic and most difficult problems of geochemistry. They are not only of theoretical, but also of enormous practical significance. The fact is that the average content of a chemical element in the technically accessible parts of the Earth refers to some of the most important factors determining its value. Prospecting, extractions of ore and fabrication of the final product of one ton of poorly distributed element costs, as a rule, much more than the recovery of the same amount of a more widely distributed element.

The first attempt to determine the average chemical composition of the earth's crust was made over 150 years ago by an English mineralogist Phillips. In the middle of the nineteenth century this problem was tackled by the American researcher F. Clarke. Assuming that the earth's crust down to the depth of 6 km consists of 95% of magmatic and 5% of sedimentary rocks, F. Clarke estimated the average contents of 50 of the most significant chemical elements.

The study related to the distribution of chemical elements in the earth's crust was further conducted by H. Washington, J. Vogt, G. Hevesi, P. Niggli, V. Ver-

nadsky, A. Fersman, A. Vinogradov, and R. Taylor. The data of the two latter authors are considered to be most substantiated, since they refer to the composition of the whole lithosphere in the way it is understood today. The average contents of individual elements in the earth's crust are called clarkes.

Clarkes are distinguished as those of the weight (mass), atomic and volumetric varieties. The mass clarkes are the average mass contents of the elements expressed in percentage value or in grammes per gramme of rock. Atomic clarkes express the percentage of the number of atoms of elements. The volumetric clarkes show what volume in percent values the given element occupies.

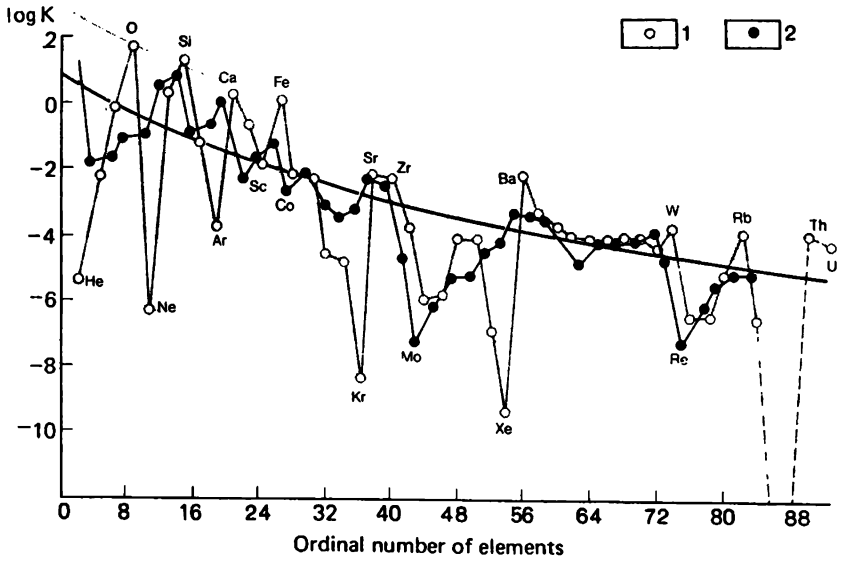
According to A. Vinogradov, the most widely spread chemical elements in the earth's crust are (%):47.2 O; 27.6 Si; 8.3 Al; 5.1 Fe; 3.6 Ca; 2.64 Na; 2.6 K; 2.1 Mg; 0.6 Ti; 0.15 H, and 0.1 C. Thus, out of 93 chemical elements discovered in the earth's crust 11 elements account for 99.99% of the mass, while the remaining 82 elements constitute only 0.01%.

The analysis of clarke contents of various chemical elements has made it possible to establish some regularities of their distribution in the earth's crust.

1. The distribution of chemical elements in the earth's crust is extremely irregular and is characterized by marked contrasts. The clarkes of some elements vary from ten per cent up to 10^{-8}% and below.

2. The distribution of chemical elements is connected with their position in the periodic system. As was already pointed out by D. Mendeleyev, the most widely spread elements of the earth's crust are situated in the beginning of the periodic system. As their number increases, the distribution of elements is irregularly diminishing. Thus, the clarkes of the first 30 elements seldom reach

FIGURE 18. Chemical elements and the logarithms of their clarkes: *1*–even; *2*–odd



hundredths of one per cent and more often are expressed in tenths of one per cent or in whole numbers. With the other elements there is a prevalence of small clarkes, which only in very rare cases go up to thousandths of one per cent. Hence, there is every reason to say that the earth's crust is remarkable for the predominance of light elements.

With the aim of representing the characteristic features relevant to the distribution of chemical elements in a more conspicuous form A. Fersman constructed a semilogarithmic graph (Fig. 18), in which we can clearly see the redundant and insufficient, or deficient, chemical elements, which are shown by the peaks going either upwards or downwards respectively.

3. Out of two adjacent elements of the periodic system the clarke of the even element is, as a rule, higher than that of the odd element. Besides, the highest clarkes are found to be with the elements the differences in the ordinal numbers of which are either equal or a multiple to 6, for example, O (8), Si (14), Ca (20), and Fe (26).

4. The main elements or the constituents of the lithosphere include only eight chemical elements. They are: O, Si, Al, Fe, Ca, Na, K, and Mg. In addition to this the leading role among them belongs to oxygen, which comprises almost 50% of the mass of lithosphere and approximately 92% of its volume. The establishing of this kind of regularities has made it possible to infer that they are presumably conditioned by the structure of atomic nuclei and their energy stability. The most widely spread (redundant) ones are the elements the atomic nuclei of which are most stable. However, the deficiency of the series of elements is, conversely, conditioned by the inconsiderable stability of the nuclei of their atoms.

There are hypotheses which also associate the regularities in the distribution of chemical elements with the characteristic features of the formation of the earth's crust as part of the Earth. It is assumed that within the period covering the emergence of the earth's crust there presumably existed such energy conditions that were favourable for the development of chemical elements with the bond energy in the nucleus, corresponding to that of the most widely spread chemical elements.

Thus, the distribution of chemical elements in the earth's crust is at present determined by two types of regularities: the conditioned properties of the nuclei of chemical elements and those associated with the characteristic features of the formation of the earth's crust as part of the Earth.

Ability of Elements to Concentrate and Disperse. The Concept of Petrogenic and Metallogenic Elements

It should be pointed out that the concept of 'distribution of chemical elements' cannot often be correlated with the concept of their availability or rarity. For instance, the clarkes of such usual elements as Cu, Zn, and Pb are many times smaller than those of Zr, V and, Y that are considered to be rare ones. What lies behind this nonconformity is the unequal ability of chemical elements to form markedly large concentrations in the earth's crust. This ability is determined by their chemical properties, which depend on the structure of outer electron shells

of the atoms, as well as on the thermodynamic conditions of the earth's crust.

The properties of all chemical elements are to a certain extent functionally dependent on their position in the periodic system. The elements that are situated close to each other within the confines of definite fields of the periodic table have very much in common as far as their chemical and physical properties are concerned, as well as their geochemical specific features. Consequently, they are found in the earth's crust together, thus giving rise to definite natural associations of chemical elements.

There is a great number of geochemical classifications of elements. The one that is the simplest and which has a general character is the classification presupposing the division of elements of the periodic system suggested by H. Washington. He divided all the elements by a horizontal line in such a way that one part of them was found to be higher, while the other below the said line.

The elements which are found in the upper part of the table were called *petrogenic* (Si, O, Ca, K, Na, Mg, Al). They compose the principal mass of the earth's crust, viz. the rock massifs and the deposits of non-metallic mineral resources.

It was suggested that the elements found in the lower part of the table should be called metallogenic. These elements are contained in the earth's crust in extremely limited quantities and compose mainly the ore deposits (Cu, Pb, Zn, Mo, etc.).

Some of those elements that are situated on the borderline between these two groups (Fe, Mn, etc.) have an ambiguous role: on the one hand, they do participate in the formation of minerals, entering into the composition of rocks as petrogenic elements, while on the other, they give rise to typical compounds of heavy metals as is characteristic of metallogenic elements.

V. Goldschmidt divided all chemical elements into groups according to stability of different types of their compounds existing in nature. His classification was based on the distribution laws of elements by three main phases of meteorites: silicate (oxygen), sulphide, and metallic. Lithophile (enriching the silicates), chalcophile (enriching the sulphides) and siderophile (enriching the metallic phase) elements are consequently distinguished. Moreover, V. Goldschmidt distinguished the atmophile elements which are characterized by a gaseous state in the Earth's surface conditions and their accumulation in the atmosphere.

Chemical Composition of the Earth's Crust and Its Characteristic Features

As a whole a comparative analysis of the chemical elements (in %) contained in the Earth (28.56 O, 14.47 Si, 1.22 Al, 37.04 Fe, 11.03 Mg, 1.38 Ca, 0.15 K, 0.52 Na) and their amount entering into the earth's crust make it possible to conclude that the latter as compared with the inner geospheres is markedly enriched by such chemical elements as O, Si, Al, K, Na, and Ca, and impoverished by Fe and Mg (as well as the heavy metals Ni, Cr, and Co).

The formation of modern chemical composition of the earth's crust is a result of processes occurring in geological time in mantle and even in the earth's core.

In the earth's crust molten masses, convectional flows of heat energy, low-melting, volatile elements, and compounds originate from the mantle.

According to A. Fersman the redistribution of substance will take place in the process of heating of the earth's crust surface of 100-140 km thickness having a homogeneous composition and formed at lower temperatures. At thermal conditions low-melting elements, oxides, and complexes will migrate up while high-melting elements will accumulate below in conformity with the law of equilibrium of compounds. As a result of it a remelting will be received as low-melting compounds melt, rise up and little by little accumulate there.

According to A. Vinogradov the earth's crust, is it were, a product of melting, degasification of mantle matter analogous to the process of the so-called 'zonal melting'. This process varies from crystallization differentiation where the factor of separation of elements is inequality of compositions of crystalline and liquid phases coexisting in a state of equilibrium. In the process of zonal melting more low-melting components will accumulate in the liquid in the upper part of heated column, while high-melting components will accumulate in the lower crystallized outer part.

When the Earth's mass reached a certain critical value, which conditioned the pressure of 140-160 GPa in the centre of the planet, the core was formed. Under the influence of the energy emitted during the decay of radioactive elements, as well as at the expense of gravitational compression there began the heating of the initially cold Earth. In the emerging sources of thermal heating the melted masses, under the influence of convectional currents, were displacing in the radial direction to the Earth's surface, melting on their way the substance of which the mantle consists. Numerous repetitions of this process brought about a regular differentiation of the substance, i.e. the removal from the mantle of relatively low-melting compounds (K_2O, Na_2O, SiO_2, and Al_2O_3), and their accumulation in the Earth's upper layer, which we call the earth's crust.

Thus, according to the mechanism of its formation the earth's crust is no more than the product of the differentiation of the mantle.

Together with the melting process involving the low-melting compounds there occurred the liberation of vapours and gases from the mantle. As a result of the degasification of the mantle matter the principal mass of gases and water that we have on Earth now was originated. At present it can be regarded as an established fact that the only source of water vapours during the condensation of which there could have been formed huge masses of the World Ocean was the earth's mantle matter. It has been estimated that up till now the quantity of water of the Earth's surface does not exceed 1% of its total reserves contained in the mantle.

The chemical composition of the earth's crust varies within the geological period, and this evolution has been going on till now. The main reasons of the changes of the chemical composition are:

1. The processes of radioactive decay, which lead to the spontaneous transformation of some of the chemical elements into those that are characterized by a greater degree of stability in conditions of the earth's crust. According to the calculations made by V. Vernadsky, in the contemporary epoch

10^6–10^{10} t of the matter entering into the earth's crust renovates its chemical composition at the expense of nuclear transformations every year.

2. The delivery of meteoric matter in the form of meteorites and cosmic dust.

3. The continuing processes of differentiation of the earth's substance leading to the migration of chemical elements from one geosphere into another.

The atoms of chemical elements in the earth's crust form various combinations with each other, mainly the chemical compounds with the atoms of other elements. The forms of their occurrence are diverse, though the main form of the existence of chemical elements in the earth's crust is mineral. Besides, in some cases they give rise to independent mineral species, while in others – they enter into crystalline lattices of other minerals in the form of admixtures.

Chapter 5 Mineral Composition of the Earth's Crust

General Information on Minerals and the Processes of Their Formation

Minerals are natural chemical compounds or individual elements, homogeneous in their chemical composition and inner structure, which are the products of various geological processes. A detailed study of the composition, structure, properties, and factors conditioning the formation of mineral is the subject of *mineralogy*.

At present about 2000 mineral species have been discovered in the earth's crust, which is considerably lower than the number of inorganic compounds received in laboratory conditions, which comprises tens of thousands of them. The main reasons that account for the limitedness of species of minerals in the earth's crust are the following: the instability of a large number of chemical compounds in the earth's crust conditions and their transition into a more stable state; restricted possibilities of thermodynamic conditions in the earth's crust (strictly definite boundaries of temperature and pressure); and relative propagation of chemical elements and their properties.

The formation of minerals in conditions of the earth's crust can take place through several means differing from each other mainly in character of mineral-forming medium.

1. By means of crystallization of natural silicate melts, or magmas, when their temperature drops below the point of solidification; it is precisely how the rock-forming minerals of deep magmatic rocks originate.

2. Through the deposition of mineral substance from aqueous solutions, either true or colloidal. These solutions can be either hot – the so-called hydrothermal solutions – from which a large number of ore minerals are formed, or cold, as, for instance, the solutions of saline lakes.

3. As a result of various transformations that take place in a solid state owing to diffusive processes.

4. Lastly, there are cases when minerals are crystallized from a gaseous state,

i. e. by means of sublimation, as is, for instance, in case with the crystals of native sulphur, that are formed on the walls of volcano craters from volcanic gases.

The processes of mineral formation given above find their expression in definite geological (endogenic and exogenic) processes, the processes of mineral formation being part and parcel of the latter. Hence, there is every reason to consider them in close association with concrete geological processes. Every single mineral is found to be stable in the given thermodynamic conditions, with the alteration of which it decomposes and transforms into a stable state under the newly created circumstances.

Among a large number of mineral species only 70 are found to be spread and enter into the composition of rocks constituting the earth's crust. They are called *rock-forming minerals.*

The vast majority of minerals are solid crystalline bodies, and only an inconsiderable part of them are discovered in solid amorphous (opal, limonite), liquid (water, mercury), and gaseous (carbon dioxide, hydrogen sulphide) states.

Minerals are characterized by regular inner structure, which finds its expression in that they have crystalline lattices, or homogeneous infinite vectorial structures, in which the material points (atoms, ions, and their groups) occupy a strictly definite geometrically regular places in space (the places of the material points are called the points of the lattices). Since all the basic properties of minerals, as well as any crystalline bodies, are determined by their inner structure and chemical composition, these questions are treated by such sciences as *crystallography* and *crystallochemistry.*

Factors Determining the Crystalline Structure of Minerals

At present, the most important factors on which the inner structure or the crystalline structure of minerals depends are: structural units of which crystalline lattices consist, their dimensions, the character of bonds with each other, and their coordination.

The Character and Size of Structural Units. Structural units of which the minerals consist include ions, atoms, and more seldom molecules; in addition to this most minerals are ionic structures. The number of structural units in minerals can be quite different, ranging from simple substances and double (binary) compounds to compounds of a highly complex composition.

The dimensions of the structural units composing the mineral are characterized by the *effective radii,* which are to be the radii of the sphere of influence of the given structural unit upon those surrounding it. The effective radii are measured in nanometers (nm), in addition to which the radii of cations (positively charged ions) are always smaller than the radii of anions (negatively charged ions).

Types of Chemical Bonds. Structural units are combined with each other by means of various kinds of chemical bonds to form minerals. The principal types are ionic, covalent, donor-acceptor, metallic, and molecular bonds.

Ionic bond is manifested in the case when during the interaction of atoms one of them attracts to the sphere of its activity one or several outer electrons,

belonging to another atom, and is thus transformed to a negatively charged ion-anion, whereas the other atom becomes a positively charged ion-cation. Ions of different charges are retained in the crystalline lattice by the force of electrostatic attraction. Ionic bonds do not have any spatial direction: each ion tends to surround itself with the maximum number of ions pertaining to the opposite sign. Predominantly, ionic bond is typical of chlorides, fluorides, and some oxides.

Covalent (atomic) bond emerges as a result of the formation of general electronic pairs at the expense of the unpaired electrons, belonging to the interacting atoms. It is also conditioned by the tendency of atoms to form an 8 stable outer electron shell. As distinct from the ionic bonds, the covalent bonds are always characterized by a definite direction. In the world of minerals the covalent bond is spread to a considerably smaller extent than ionic bond. We find it only in minerals, the molecules of which are formed by atoms of one chemical element. What is more widely spread is the transient ionic and covalent type of bond.

Donor-acceptor bond consists in the use of already existing pairs of electrons of one atom, viz. the donor, by the other atom – the acceptor. The electrons then are found to be for a certain period of time in the shell of one atom and for some time in the shell of the other, thus forming a bond between themselves. The donor-acceptor bond is most typical of some of the sulphides and their analogues.

Metallic bond is most widely represented by native metals (copper, gold, and silver). In compounds with metallic bond each atom gives away electrons that participate in the bond and that move freely in the form of 'electron gas' between positively charged ions. The metallic bond does not have any direction and every single ion tends to surround itself with the maximum number of neighbours.

Molecular bond manifests itself as a result of the interaction between the neutral molecules, within which other types of bonds are established. This bond is rather weak and is determined by the so-called Van der Waals forces. Among minerals this type of bond is not widely spread. According to the degree of homogeneity of chemical bonds all minerals can be divided into *homodesmic* and *heterodesmic* compounds. Homodesmic compounds include minerals, in which the bond of only one type is established. For instance, in halite (NaCl) and fluorite (CuF_2) all the bonds are ionic, in diamond (C) they are covalent, and in native copper (Cu) the bonds are metallic. When minerals contain different types of chemical bonds they are referred to heterodesmic compounds. For instance, gypsum ($CaSO_4 \times 2H_2O$) is characterized by covalent bonds between sulphur and oxygen in ion $[SO_4]^{2-}$, whereas cations Ca^{2+} are connected with the sulphate ion by means of ionic bonds, while the molecules of water are combined with $CaSO_4$ with the help of molecular bonds.

The Coordination of Structural Units. Forming the crystalline lattice the structural units of minerals surround themselves with a definite number of neighbours, situated in a corresponding manner. The number of the nearest neighbours of an atom or an ion equally arranged in relation to it in the crystalline lattice is called *the coordination number*. The values of coordination numbers in the crystals of minerals varies from 2 to 12, the most widely spread

coordination numbers being 6, 4, 8, and 12. The coordination number depends on the size of the structural units, the type of chemical bond, as well as the conditions in which minerals are formed.

The coordination of atoms, in its turn, conditions the stability of the bonds, which, with the diminishing of the coordination number grows and causes the corresponding decrease in interatomic distances.

Speaking of the coordination number, we imagine the structural units of the crystalline lattices of minerals (ions, atoms, etc.) in the form of elastic adjoining spheres. It has been taken for granted that they fill the space according to the principle of the closest cubic or closest hexagonal packing. In the case of the closest packing the balls of equal size occupy 74.05% of the volume, the remaining part of the space being filled with voids, which can be of two types: tetrahedral (between 4 balls) and octahedral (between 6 balls). As anions by their dimensions are usually greater than cations, it is precisely they that create the closest packing, within the voids of which cations are situated.

This kind of representation or modelling of the crystalline structures of minerals given here is being conducted at present with the help of the three basic methods (Fig. 19):

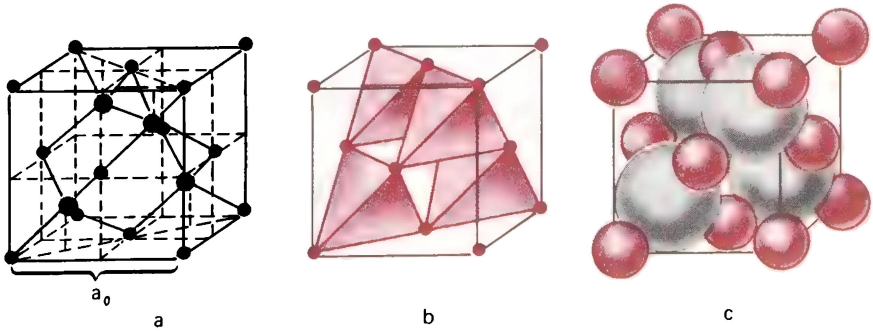
(1) in the form of the closest packing of anions and cations of corresponding dimensions. This method is not visual, since only one layer of balls (one flat net) can be seen;

(2) in the form of the so-called discharged models, when instead of the balls of the closest packing only their centres are represented. These models possess perfect visual qualities, though give no information on the degree to which the space is filled;

(3) in the form of various kinds of polyhedra (tetrahedra, octahedra, etc.) cut off from the closest packing of anions and filled with cations. These are the so-called Paulling models (named after L. Paulling, the scientist who suggested them).

Structural Motifs.The character of chemical bonds and their direction are determined by the predominant trend in the distribution ('cohesion') of atoms, ions and their groups (radicals) in the crystalline lattice of a mineral, or, in other

FIGURE 19. Three types of modelling the crystalline structure of sphalerite (ZnS): *a* – discharged model; *b* – Pauling model (the centres of ions of sulphur are situated within each of the tetrahedra); *c* – the closest packing (black balls represent the ions of zinc, white ones indicate ions of sulphur)



words, by its *structural motif*. The following basic types of structural motifs are distinguished.

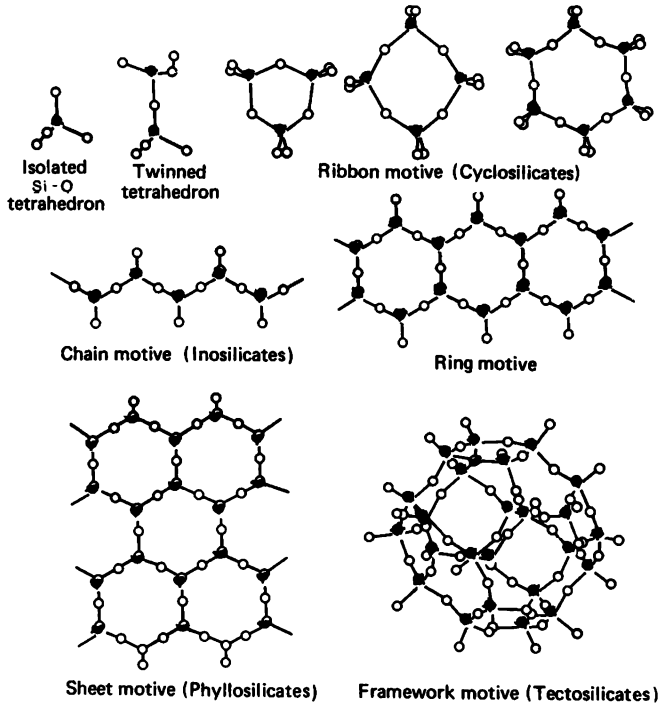
1. *The coordination motif* is characterized by proportional distribution of atoms or ions in crystalline structures. It is typical of homodesmic minerals and is remarkable for the proportional distribution of chemical bonds in three dimensions. The coordination motif with an essential ionic bond is established in halite (NaCl), with a marked covalent bond in diamond (C), and with the metallic bond in native metals. The other types of structural motifs are characteristic of heterodesmic minerals.

2. *The island motif* is characterized by the presence in the structure of individual groups of atoms (radicals) the bonds within which are always more stable than their bonds with the atoms and ions that surround them. The radicals can be either linear, triangular, pyramidal, tetrahedral, or octahedral. Island structures are typical of carbonates, sulphates, and some of the silicates.

3. *The ring motif* is found relatively rare in the crystalline structures of minerals. It is characterized by the combination of isolated groups of atoms in a ring of various configuration (three-, four-, six-, and eight-member ones). Minerals with the ring structure can be exemplified by native sulphur and beryl.

4. *The chain motif* is distinguished by a clearly expressed linear direction of the

FIGURE 20. Types of structural motifs in the crystals of minerals as exemplified by silicates



most stable bonds in the crystalline lattice. It is characterized by the presence of 'infinite' groups of atoms arranged in the form of chains. Besides, the bonds within the chains are always more stable than those between them. Chains can be either single, or doubled, resulting from the reflection of the single chains in the plane of symmetry. This kind of double chains are also called ribbons, and the structures of which they are typical are referred to as ribbon structures. The chain motif is characteristic of a large number of silicates, sulphides and oxides.

5. *The layer motif* is characterized by the two-dimensional distribution of the most stable bonds in a structure, i.e. by the arrangement of structural units (atoms, radicals) in a plane. This gives rise to the presence of groups of atoms in them comprising 'infinite' layers, the bonds between which are less stable than within them. In the cross section the layers can be either simple, i.e. consisting of one network of atoms, or complex – those that comprise several net planes. The layer motif is developed in minerals that belong to the classes of silicates, oxides, sulphates, and sulphides.

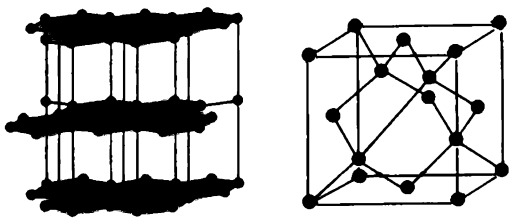
6. *The framework motif* emerges in the case when the radicals are connected with each other through common apexes in the form of a three-dimensional framework. It is characterized by the regular spatial distribution of stable interatomic bonds. Framework minerals include many alumosilicates, in particular feldspars as well as quartz.

The most important structural motifs of heterodesmic minerals are exemplified by silicates, where the crystalline structure is based on radical $[SiO_4]^{4-}$ or Si-O-tetrahedron (Fig. 20).

Most of the minerals have an island structure; minerals of chain structure are found less often; and only about 50 mineral species possess a framework structure. But it is precisely the framework minerals, owing to the high degree of stability of their lattices, that are more widely spread in the earth's crust and which include the most significant rock-forming minerals.

Polymorphism. Every mineral has its own structure – a crystalline lattice with a given inner and outer symmetry – typical of it alone. However, there have been cases when a substance of one and the same composition can have various crystalline structures. This phenomenon, discovered by E. Mitscherlich in 1920 has acquired the name of polymorphism. The term polymorphism is attributed to the property of compounds and simple substances to be crystallized in

FIGURE 21. Polymorphic modifications of carbon:
a – graphite (hexagonal); *b* – diamond (cubic)



a b

compliance with the external factors in various structural types. Polymorphism is widely spread in the world of minerals. A striking example of this phenomenon are the polymorphic modifications of carbon, viz. graphite and diamond. Graphite is crystallized in the hexagonal system, while the cubic system has the similar effect upon diamond (Fig. 21). Consequently, both these minerals, the chemical composition of which is the same, have absolutely dissimilar properties.

The varieties of the given crystalline substance that are stable under given physicochemical conditions are called polymorphic modifications. Examples of polymorphic modifications of minerals are: disthene and sillimanite, calcite and aragonite, sphalerite and wurtzite, pyrite and marcasite.

Chemical Composition of Minerals

The Characteristic Features of Chemical Composition. Most of the chemical elements of the periodic system enter into the composition of minerals, i.e. are *mineral-forming*. However, their role in the composition of minerals is by no means the same. According to their quantitative and qualitative functions in the composition of minerals all mineral-forming elements can be divided into two groups:

(1) *species-forming*, or those that give rise to independent mineral species (Si, O, H, Al, Ca, Na, Mg, Cu, Pb, S, and others);

(2) *trace*, i.e. the ones that do not give independent minerals and, as a rule, enter into the structure as their constituents (Rb, Hf, Re, Ra, Ro, etc.).

In their turn the species-forming elements, depending on the number of mineral species that they form, can be subdivided into *the main* ones, which form a considerable number of mineral species (indicated in brackets); they are, for instance, O (1364), H (908), Si (432), Al (320), Cu (184), Rb (178), etc., and *the minor* and *accessory elements*, the number of mineral species for which is not great, e.g. Ni (49), Bi (61), Li (24), Ag (50), U (59), Cr (17), and Hg (16). No strict correspondence between the clarkes of chemical elements and the number of mineral species formed by them has been established. The different role of mineral-forming elements depends on their chemical properties, as well as on the physicochemical conditions of mineral-forming processes, which determine the predominance of certain kinds of stable compounds of the given element.

Minerals are represented by the following main types of chemical compounds:

(1) simple substances or native elements, e.g. native sulphur (S), graphite (C), native copper, gold and platinum (Cu, Ag, Pt), etc.;

(2) oxides and hydroxides, e.g. corundum (Al_2O_3), rutile (TiO_2), cuprite (Cu_2O), and others;

(3) by salts of various oxygen-containing and oxygen-free acids, representing the most widely spread type of chemical compounds in the world of minerals. e.g. halite (NaCl), pyrite (FeS_2), calcite ($CaCO_3$), barite ($BaSO_4$), forsterite ($MgSiO_4$), anhydrite ($CaSO_4$), etc.

A large number of salts are characterized by the groups of atoms which participate in chemical reactions as an integral whole and are called complex anions, or *radicals*. The principal radicals in minerals are: [SiO_4] in silicates,

$[CO_3]$ in carbonates, $[PO_4]$ in phosphates, $[SO_4]$ in sulphates. Complex anions are distinguished from the simple ones by larger dimensions and the presence of stable chemical bonds within these complexes.

Minerals fall into compounds of invariable composition (definite compounds) and those of variable composition (indefinite compounds). In any genetic conditions *definite compounds* retain one and the same quantitative relationship of mineral-forming elements in their structure. This group of minerals includes, for instance, halite (NaCl), calcite ($CaCO_3$), hematite (Fe_2O_3), quartz (SiO_2), cuprite (Cu_2O), and others.

With *the indefinite compounds* the composition can change within certain limits (covering the region where the crystalline lattice of the given structure at the given temperature and pressure conditions can exist), in addition to which the variations in the composition cannot be accounted for by foreign mechanical admixtures. This group comprises the vast majority of minerals.

Isomorphism.The ability of minerals to form compounds of variable composition is based on isomorphism, a phenomenon involving the replacement of atoms and ions in the crystalline lattices of minerals without hampering their structure. The thus formed substances are called *isomorphic mixtures*, or *solid solutions*. The possibility of isomorphic replacements is conditioned on the one hand by the similarity of properties of atoms and ions themselves (dimensions, coordination, conditions of chemical bond), and, on the other hand, by some of the parameters of mineral-forming processes (temperature, pressure, and concentration of components). Thus, for instance, in conditions of high temperatures the isomorphic replacement of components takes place within markedly greater limits than when the temperatures are low. A considerable unsaturation of the mineral-forming medium of some elements does not allow them to form crystalline lattice for their own minerals, which results in their scattering in the other mineral lattice in the form of isomorphic admixtures.

Depending on the quantitative relations of the elements that replace each other, isomorphism is either *complete*, or *perfect*, and *partial* or *imperfect*. In the case of complete isomorphism the miscibility of components is made possible in any of the quantitative ratios. An example of complete isomorphism is the group of plagioclases, which represents a continuous isomorphic series, the extreme members of which are albite $Na[AlSi_3O_8]$ and anorthite $Ca[Al_2Si_2O_8]$ with the replacement scheme $NaSi \rightarrow CaAl$. Complete isomorphism in the class of oxides is also found in the series columbite $(Fe, Mn)Nb_2O_6$ – tantalite $(Fe, Mn)Ta_2O_6$ with the replacement scheme $Nb \rightarrow Ta$.

In the case of incomplete isomorphism the miscibility of the components becomes possible only in given quantitative relationships. The cases of incomplete isomorphism are much greater in number and they can be exemplified by calcite $CaCO_3$, where up to 22% Ca can be replaced by Mg, fluorite CaF_2, in which up to 17% Ca is replaced by Y according to the scheme $3Ca \rightarrow 2Y$, rutile TiO_2, where approximately 30% Ti can be replaced by Nb (+ Fe) according to the scheme $3Ti \rightarrow 2Nb + Fe$, and a large number of others.

In minerals with a substantially ionic type of bond we also distinguish *isovalent* and *heterovalent* kinds of isomorphism.

In cases of isovalent isomorphism ions with the same charges are reciprocally

replaced. Thus, for instance, $K^{1+} \rightarrow Rb^{1+}$ in feldspars, $Mo^{4+} \rightarrow Re^{4+}$ in molybdenite, $Ba^{2+} \rightarrow Sr^{2+}$ in barite, $Ca^{2+} \rightarrow Mn^{2+}$ in granites, etc. When isomorphism is heterovalent we find that the interchanging of ions are of different valence, but the replacement takes place with the compensation of charges, i.e. with the electrostatic balance retention of the lattice. The replacements of this kind are discovered in plagioclases ($Na^{1+}Si^{4+} \rightarrow Ca^{2+}Al^{3+}$), biotite ($3Mg^{2+} \rightarrow 2Al^{3+}$), nepheline ($2Na^{1+} \rightarrow Ca^{2+}$), chalcosine ($2Cu^{1+} \rightarrow Cu^{2+}$), pyrrhotite ($3Fe^{2+} \rightarrow 2Fe^{3+}$) and many other minerals. In addition to this, the interchanging of ions occurs most successfully when the difference in the charges of ions does not exceed 1.

Formulae of Minerals. It is customary to express the chemical composition of minerals with the help of *empirical* or *structural formulae*. The former serve to express the quantitative chemical composition of minerals, without giving any idea of the combinations and bonds of chemical elements with each other. In structural formulae, which are more widely spread in mineralogy, not only the chemical composition of minerals is taken into account, but also the type of chemical combination and the interrelationships of individual elements.

It is usual that in structural formulae radicals are singled out by means of square brackets, and round brackets are employed for elements that are closely connected with each other. For instance, the empirical formula of disthene is expressed either as Al_2SiO_5 or as $Al_2O_3 \cdot SiO_2$. The structural formula is $Al_2[SiO_4]O$. Structural formulae are particularly important for minerals of complex composition, so the formula of augite has the expression $Ca(Mg, Fe, Al)[(Si, Al)_2O_6]$, that of topaz is $Al_2(F, OH)_2[SiO_2]$, and so on.

Isomorphic groups of elements in the descending order of their quantity are enclosed in round brackets and are separated from each other by commas; for example, the formula of sphalerite is $(Zn, Fe, Mn, Cd, Ge, In, Te)S$, wolframite has the formula $(Mn, Fe)WO_4$, olivine is expressed by $(Mg, Fe)_2[SiO_4]$, etc.

If the mineral contains elements of different degree of oxidation, they are written down separately with their valence indicated: thus the formula of magnetite has the expression $Fe^{2+}Fe^{3+}O_4$, the formula of hornblende is $Ca_2Na(Mg, Fe^{2+})_4(Al, Fe^{3+})(OH)_2[(Si, Al)_4O_{11}]_{22}$. The molecules of water in crystal hydrates are written at the end of the formula, and are connected by a point: e.g. $CaSO_4 \cdot 2H_2O$ – gypsum.

Basic Principles of Geometric Crystallography

Crystals are solid bodies in which the material particles (atoms, ions, and molecules) are regularly arranged, in the form of nodes of space lattices. The surface of crystals is restricted by planes, or *faces* that are intersected along straight lines called *edges*. The points at which edges intersect form *apexes*. It should, however, be mentioned that the regular inner structure is shared by a large number of solid bodies that do not have any geometrically proper outer form.

The crystalline state of a substance is found to be more stable as compared with the amorphous state, since the regular arrangement of any particle in the structure is in correlation with the minimal degree of internal energy.

The main properties of crystalline bodies are: anisotropy, homogeneity, and the autonomous ability to form faces.

Anisotropy is the variation of the properties of a substance with the change in direction. It is conditioned by various reticular density of the crystalline lattice in different directions.

A very good example of anisotropy is mica. The crystalline plates of this mineral are easily dissected into planes, parallel to its plasticity. In transverse directions it is not easily to break up the micaceous plates.

One more typical example of anisotropy is disthene, which is characterized by markedly variable degree of hardness along different directions.

Homogeneity consists in that any two parts of one and the same crystal possess similar properties (along parallel directions). Solid amorphous bodies can also be homogeneous and even anisotropic.

The ability to form faces, i.e. to acquire the form of regular polyhedra, or crystals, in the conditions of free growth in the favourable medium, is associated with the anisotropy of crystals: the attraction of the deposited particles during the growth of the crystal is the same along any one of the faces and changes in the course of its transition to some other direction, or to another face.

The Symmetry of Crystals and Its Elements.The branch of science that deals with the geometric description of crystals and their internal arrangement is called *crystallography*.

The relationship between the inner structure and the outer form of crystals finds its expression in one of the fundamental laws of geometric crystallography – *the law of constant angles*, in accordance with which the angles between corresponding faces (or edges) in all crystals of one and the same substance remain constant. In studying the geometry of crystals we often make use not of genuine crystals, the cutting of which is, as a rule, far from perfection, but of geometrically regular polyhedra, representing ideal models of certain crystals.

Symmetry. As far as crystals are concerned symmetry is a regular recurrence in space of similar faces, edges and angles of a figure. The characterization of the said regularity presupposes the use of imaginary auxiliary forms, such as points and straight planes, in respect of which the equal parts of figures regularly occur. These forms are called *elements of symmetry*.

The basic elements of symmetry are the centre, the plane, and the axis of symmetry. *The centre of symmetry*, or *the centre of inversion* (*C*) is the point within a crystal, in which all the lines connecting the corresponding points on the surface of the crystal are intersected and divided in two. Thus, if on one side of *C* we have the apex of the polyhedron, then on the other side at the same distance from the centre there should be the same apex. The same can be said in reference to other points on the faces and edges of a crystal. In those cases when the crystal has the centre of symmetry each of its faces should necessarily be correlated with another face that is equal and parallel (or conversely parallel) to the first one.

The plane of symmetry (*P*) is the imaginary plane that divides the figure into two symmetrically equal parts, situated in respect of each other as the object and its mirror reflection. The planes of symmetry can either pass through the mid-points of faces and edges, perpendicularly to them, or along the edges, thus forming equal angles with similar faces and edges. A very well known example is

a polyhedron, or a cube (hexahedron), which has the maximum number of planes (9). Their arrangement is shown in Fig. 22.

The axis of symmetry is the straight line rotating round which there recur equal parts of the figure (the latter is self-compatible with its original position in space). The number of self-compatibilities at the turn on 360° determines the order of the axis of symmetry (n).

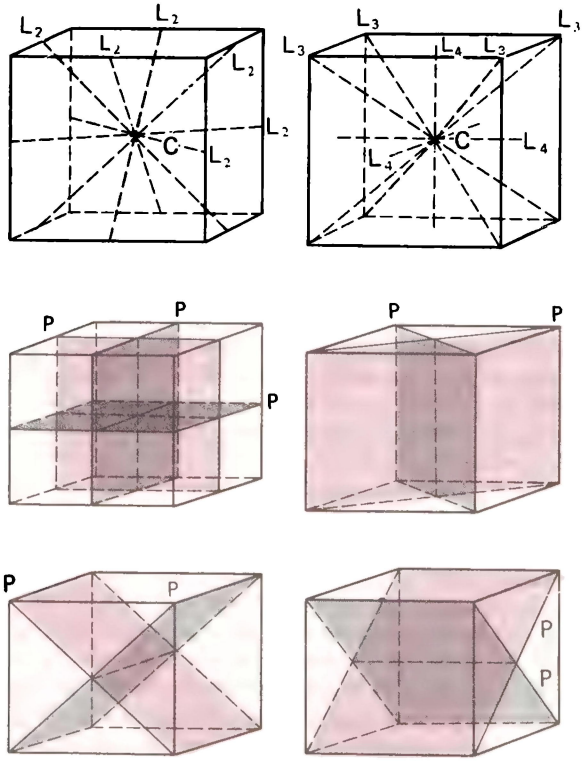
To designate the axes it is customary to employ the Latin letter L. The order of axis is shown with a small figure placed to the right of the letter (L_n), while the number of axes of the given order, as well as the number of planes, are indicated by a numerical coefficient, which comes before the letter, e.g. $3L_2$.

As a result of their lattice structure crystals can have the axes of the first (they are not taken into consideration in crystallography), the second, the third, the fourth, and the sixth orders (L_2, L_3, L_4, L_6).

The axes of the fifth order and of the order higher than the sixth do not exist in crystals. The axes of the third, the fourth, and the sixth order are called the axes of the highest order.

The angle of minimum rotation which makes the figure acquire a self-compatible state is called the angle of elementary rotation (α). The elementary angle of

FIGURE 22. The arrangement of axes and planes of symmetry in a cube (hexahedron)



rotation of any axis of symmetry is contained an integer number of times in $360° : \alpha = 360°/n$.

The directions of axes of symmetry in crystalline polyhedra should be found in the centres of opposite faces of regular form, in the mid-points of opposite edges, and in the apexes, where we have a symmetrical convergence of 3, 4, or 6 faces. The axes of symmetry can also pass through the characteristic points of different elements of cutting; for instance, through the apex and centre of the opposite face, and through the apex and mid-point of the opposite edge (see Fig. 22). Besides simple axes of rotation the crystals can have complex, or the so-called inversion axes (L_i).

The inversion axis is a straight line rotating round which at a given angle with the consequent reflexion in the central point of the figure as in the centre of inversion, the figure coincides with itself. Thus, the inversion axis represents, as it were, the combination of the simple axis of rotation and the centre of inversion acting together. It should be mentioned that in crystals possessing inversion axes the centre of inversion, as an independent element of symmetry, is usually not found. In most cases crystals have inversion axes of the fourth and the sixth orders (L_{i_4} and L_{i_6}).

To determine the symmetry of crystals we also employ the concept of unit direction, which was introduced by E. Fedorov. The *unit direction* is the only unrecurrent direction in a crystal. As distinct from it the recurrent directions, associated with the elements of symmetry, are called *symmetrically equal ones*. For instance, in a prism the unit direction is the one that is parallel to the faces of a prism and passing through the centre of symmetry. In a cube any direction is repeated several times, and it is always correlated with some other direction similar to it and equal in value. Hence, there are no unit directions in a cube, and what we have instead are symmetrically equal directions. The more symmetrical the crystal is the fewer unit directions it has, until they disappear altogether.

Types of Symmetry, Crystallographic Systems and Categories. Elements of symmetry are present in crystals not only by themselves, but also in definite combinations with each other.

The combination of all the elements of symmetry of the given crystalline polyhedron is called its *type of symmetry*. In addition to this, not any arbitrary combination of the elements of symmetry is possible. There are some theorems, which help to deduce all possible combinations of the elements of symmetry in accordance with strict mathematical methods. Only 32 types of symmetry are possibly found in crystallography (Table 3). They were first deduced by the Russian scientist A. Gadolin in 1867. All the known types of symmetry are subdivided into seven crystallographic systems.

The system is a group which includes several types of symmetry possessing one or several elements of symmetry with the number of unit directions being equal. In the order in which the degrees of symmetry increase the systems can be graded in the following: *triclinic, monoclinic, orthorhombic, trigonal, hexagonal, tetragonal* and *isometric*. In their turn the systems are grouped into three categories, viz. *the lower, middle,* and *the higher*. Their characterization is given in Table 4.

The Forms of Crystals. According to the form of their outer cutting, crystals can be divided into two groups. The first group comprises those that consist of

TABLE 3. Crystals (Types of Symmetry)

Category	System	Types of Symmetry						
		primitive	central	planal	axial	planal and axial	inversion and primitive	inversion and planal
	Triclinic		C					
Lower	Monoclinic			P	L_2	L_2PC		
	Orthorhombic			$L_2 2P$	$3L_2$	$3L_2 3PC$		
	Trigonal	L_3	L_3C	$L_3 3P$	$L_3 3L_2$	$L_3 3L_2 3PC$		
Middle	Tetragonal	L_4	L_4PC	$L_4 4P$	$L_4 4L_2$	$L_4 4L_2 5PC$	$L_{i_4}(\vec{=} L_2)$	$L_{i_4}(\vec{=} L_2) 2L_2 2P$
	Hexagonal	L_6	L_6PC	$L_6 6P$	$L_6 6L_2$	$L_2 6L_2 7PC$	$L_{i_6}(\vec{=} L_3 P)$	$L_{i_6} 3L_2 3P$ $(= L_3 3L_2 4P)$
Higher	Isometric	$4L_3 3L_2$	$4L_3 3L_2 3PC$	$3L_{i_4} 4L_3 6P$	$3L_4 4L_3 6L_2$	$3L_4 4L_3 6L_2 9PC$		

TABLE 4. Characteristic Features of Crystallographic Systems and Categories

Category	System	Number of unit directions	Characteristic elements of the symmetry	Examples of minerals crystallized in the given system
Lower	Triclinic	All	C or none	Albite, anorthite, microcline, disthene
Unit direction is 3 and more; no axes of symmetry of the order higher than the second	Monoclinic	Numerous	Recurrent elements of the symmetry are absent	Orthoclase, talc, epidote, hornblende, gypsum, arsenopyrite
	Orthorhombic	Three	$L_2 2P$; $3L_2$; $3L_2 3PC$	Olivine, topaz, barite, antimonite, marcasite
Middle	Trigonal	One, coincides with L_3	L_3	Calcite, dolomite, magnesite, hematite, cinnabar
One unit direction; coincides with the only axis of the higher than the second order	Tetragonal	One, coincides with either L_4 or L_{i_4}	L_4 or L_{i_4}	Chalcopyrite, cassiterite, scheelite
	Hexagonal	One, coincides with L_6	L_6 or L_{i_6}	Nepheline, beryl, apatite
Higher No unit directions; Presence of several axes of symmetry of the order higher than the second	Isometric	None	$4L_3$	Garnet, halite, sylvite, fluorite, diamond, chromite, pyrite, galenite

symmetrically arranged faces identical in form and dimensions. These, for instance, are cube and octahedron (Fig. 23). The second group indicates crystals that have faces of different size and contours.

For instance, the commonly known polyhedron in the form of a small brick shows three types of equally in pairs rectangular faces. Polyhedra of the first group represent the simple forms, while those pertaining to the second one exemplify the combinations of forms of this type.

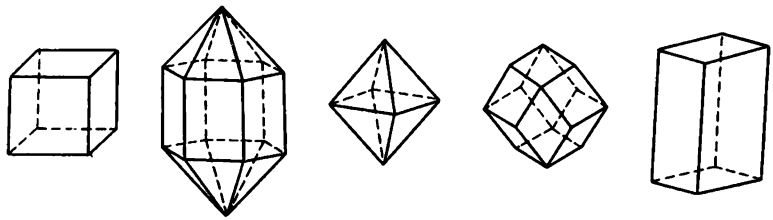
The simple form is the combination of faces connected with each other by the elements of symmetry. Hence, the faces of one simple form, which in the ideally developed crystals should be the same in contours and size, being associated with

the elements of symmetry, can be deduced from one group of faces by means of the activity of these elements.

All in all, there are 47 types of simple forms known in crystallography (Fig. 24). All of them are deduced from strict mathematical rules and are based on 32 types of symmetry.

The combination is defined as the set of two or several simple forms. Combinations cannot be deduced from one original plane, and, consequently, they have faces that are different in form, size, and other properties. The number

FIGURE 23. Forms of crystals:
a, *c*, *d* – simple crystals; *b*, *e* – combinations of simple forms



of combinations can be infinite. Every single crystallographic system is characterized by its own set of simple forms, and only some of them, as for instance, monohedron and pinacoid, are 'transitory' (see Fig. 25).

Mineral grains, entering into the composition of rocks and ores, do not usually have regular crystallographic contours. This finds its explanation in that their growth, as a rule, takes place in restricted circumstances. On the other hand, the general shape of crystals is commonly retained, and it can often serve as a distinguishing feature by which it is possible to establish their group of symmetry.

Forms of Natural Mineralization

In natural conditions minerals are found either in the form of accumulations of mineral grains, called mineral aggregates, or much more seldom in the shape of individual crystals and their growths (Fig. 26). The form of mineral aggregates is primarily determined by the conditions of mineralization, that is why one and the same mineral can yield aggregates of various forms.

Monocrystals are unique, well faced crystals of minerals formed in the conditions of free growth (in fissures, voids, and other cavities). According to the relationship of the three basic dimensions, determining the shape of crystals, they are divided into isometric, or those that are characteristic of galenite, pyrite, garnet, and halite; elongated in one direction, which, depending on the form of crystals can be prismatic, columnar, and acicular (typical of quartz, antimonite, hornblende, and others); elongated in two directions, e. g. tabular, or platy, and scale, which are characteristic of micas, chlorite, gypsum, etc.

FIGURE 24. Simple forms of crystals

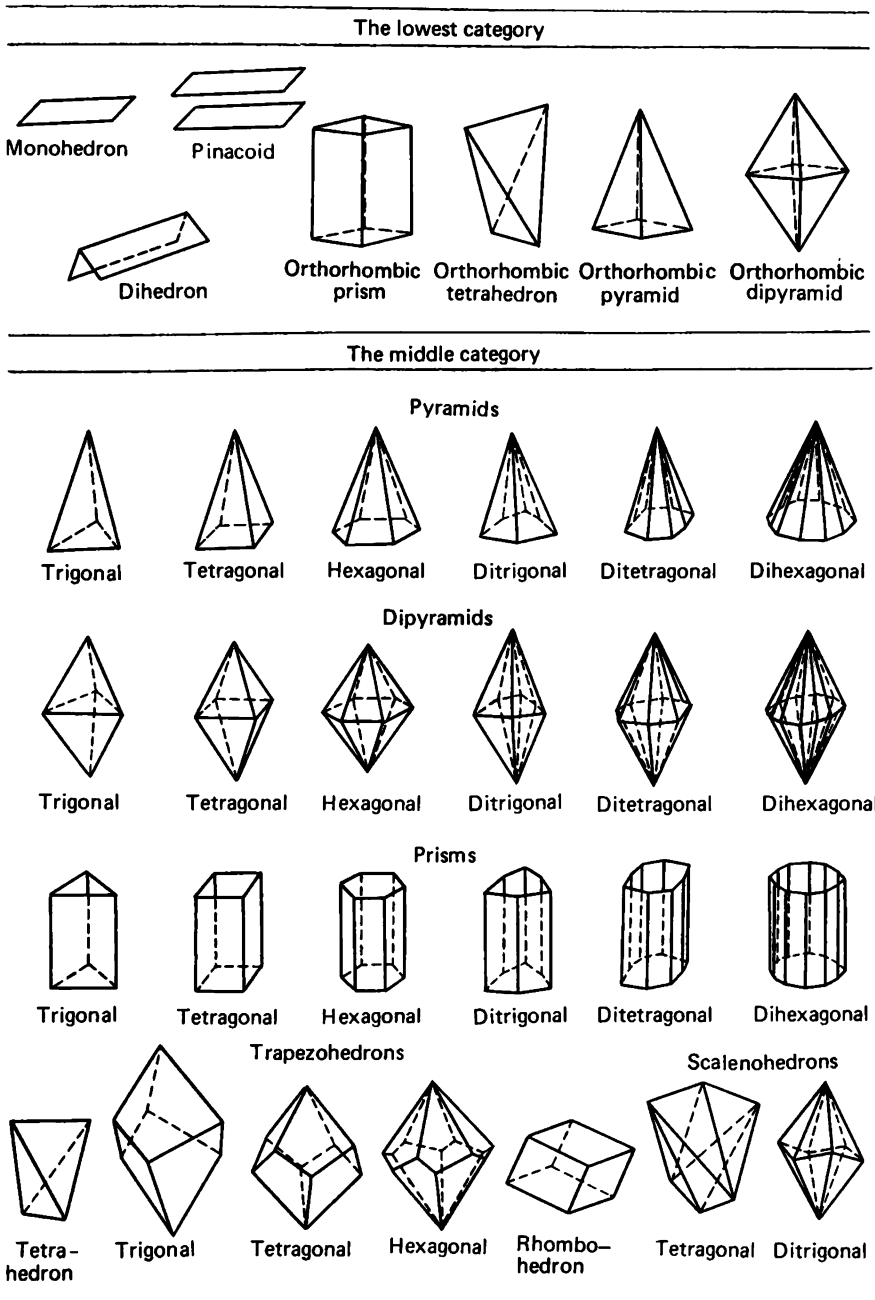


FIGURE 24. (*Continued*)

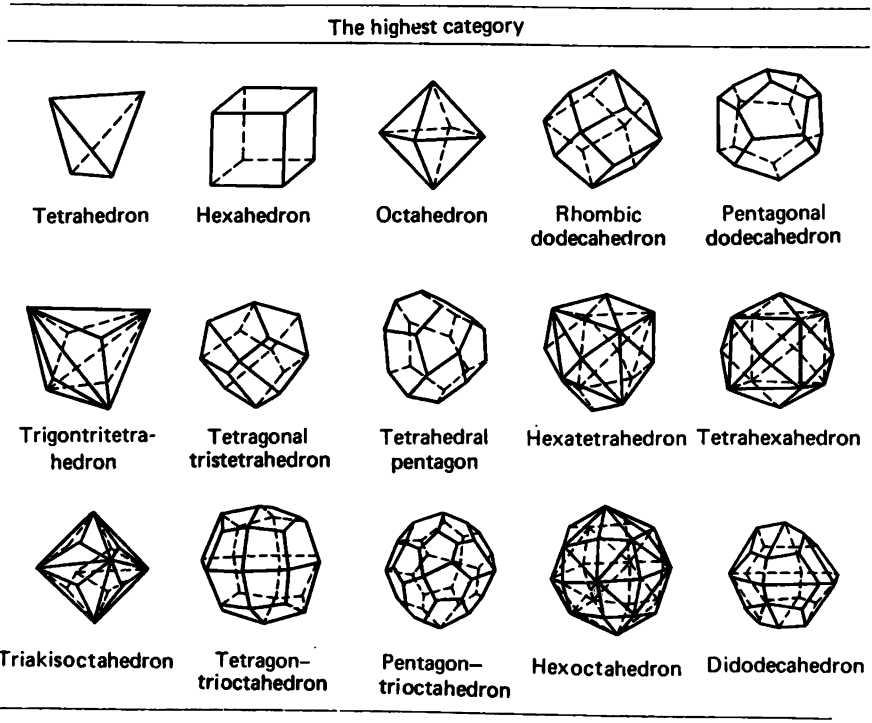


FIGURE 25. Combinations of simple forms (examples)

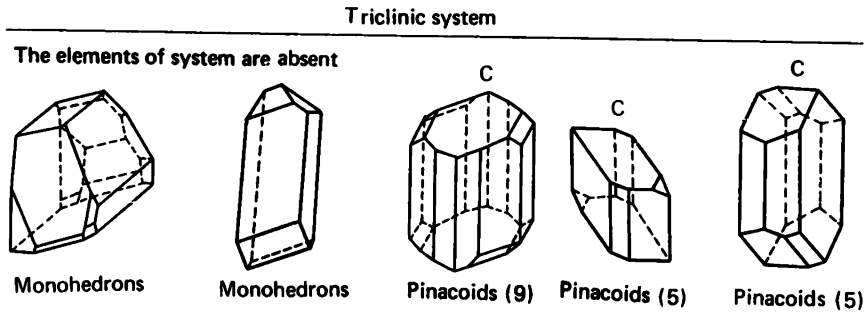
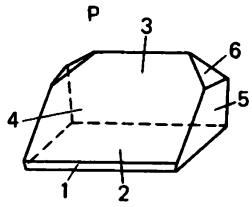
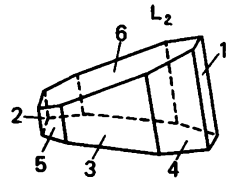


FIGURE 25. *(Continued)*

Monoclinic system



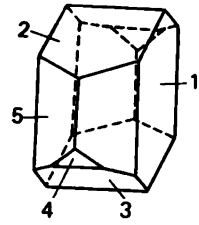
1, 2, 3, 4–monohedrons
5–pinacoid
6–dihedron



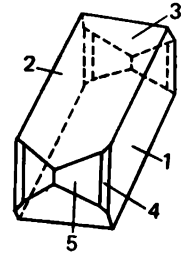
1,2–monohedrons
3–pinacoid
4, 5, 6–dihedrons

L_2PC L_2PC L_2PC

1–pinacoid
2, 3–orthorhombic prism

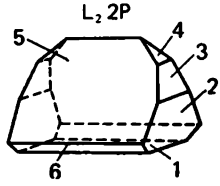


1, 2, 3, 4– pinacoid
5-orthorhombic prism

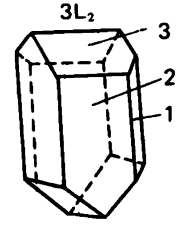


1, 2, 3–pinacoid
4, 5–orthorhombic prism

Orthorhombic system

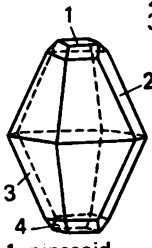


1–monohedron
2–pinacoid
3, 4, 5, 6–dihedrons



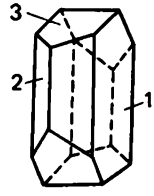
1–pinacoid
2–orthorhombic prism
3–orthorhombic tetrahedron

$3L_23PC$



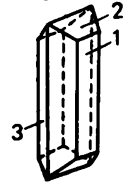
1–pinacoid
2–orthorhombic prism
3,4–orthorhombic dipyramid

$3L_23PC$



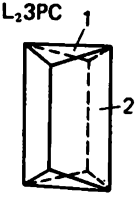
1–pinacoid
2,3–orthorhombic prism

$3L_23PC$



1–pinacoid
2,3–orthorhombic prism

$3L_23PC$

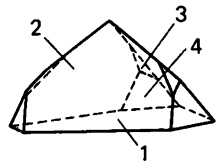


1, 2–orthorhombic prism

FIGURE 25. (*Continued*)

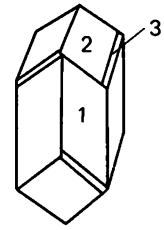
Trigonal system

L_3



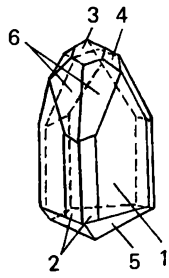
1–monohedron
2, 3,4–trigonal pyramid

L_3C

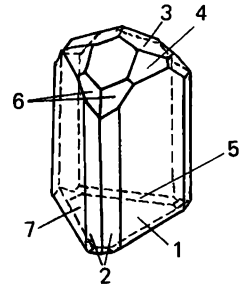


1-hexagonal prism
2, 3–rhombohedron

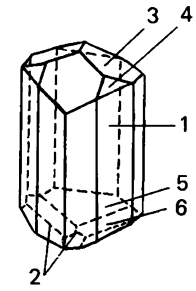
L_3 3P



1–trigonal ptism
2–ditrigonal prism
3, 4, 5–trigonal pyramid
6–ditrigonal pyramid

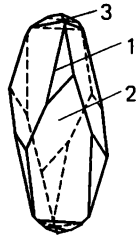


1–trigonal prism
2–ditrigonal prism
3, 4, 5–trigonal pyramid
6–ditrigonal pyramid
7–monohedron



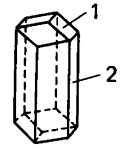
1–trigonal prism
2–ditrigonal prism
3, 4, 5, 6–trigonal pyramid

$L_3 3L_2$

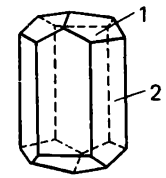


1, 2, 3-trapezohedron

$L_3 3L_2 3PC$



1-rhombohedron
2-hexagon



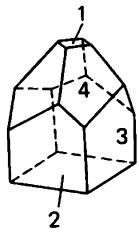
1-rhombohedron
2-hexagon

FIGURE 25. (*Continued*)

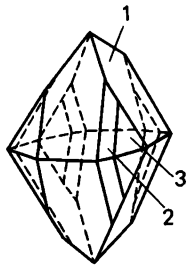
Tetragonal system

L_4PC

L_4

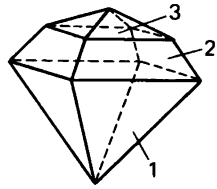


1, 2–monohedron
3–tetragonal prism
4–tetragonal prism



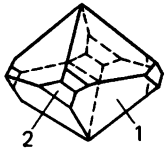
1, 2, 3–tetragonal dipyramid

L_4 4P



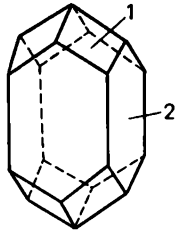
1, 2, 3–tetragonal pyramid

$L_4 4L_2$



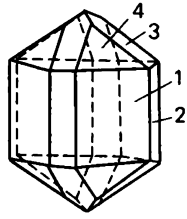
1 –tetragonal dipyramid
2–tetragonal trapezohedron

$L_4 4L_2 5PC$



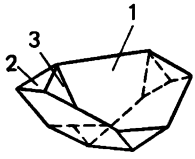
1–tetragonal prism
2–tetragonal dipyramid

$L_4 4L_2 5PC$



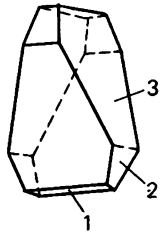
1, 2 –tetragonal prism
3, 4, –tetragonal dipyramid

L_{i_4}

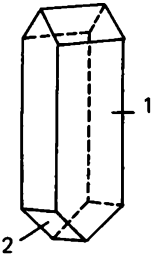


1, 2, 3–tetragonal tetrahedron

$L_{i_4} 2L_2 2P$



1–pinacoid
2, 3–tetragonal tetrahedron

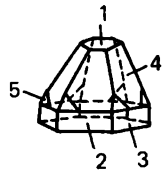


1–tetragonal prism
2–tetragonal tetrahedron

FIGURE 25. (*Continued*)

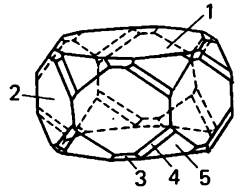
Hexagonal system

L_6



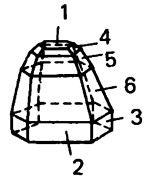
1,2–monohedron
3– hexagonal prism
4, 5–hexagonal pyramid

L_6PC



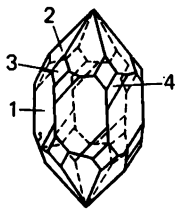
1–pinacoid
2–hexagonal prism
3, 4, 5–hexagonal dipyramid

$L_6 6P$



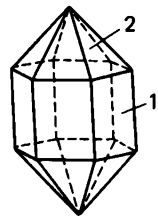
1,2–monohedron
3– hexagonal prism
4, 5–hexagonal pyramid

$L_6 6L_2$



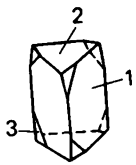
1–hexagonal prism
2, 3–hexagonal dipyramid
4–hexagonal trapezohedron

$L_6 6L_2 7PC$



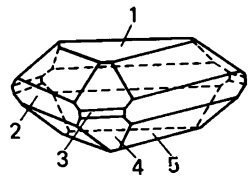
1–hexagonal prism
2–hexagonal dipyramid

$L_{i_6}(L_3P)$



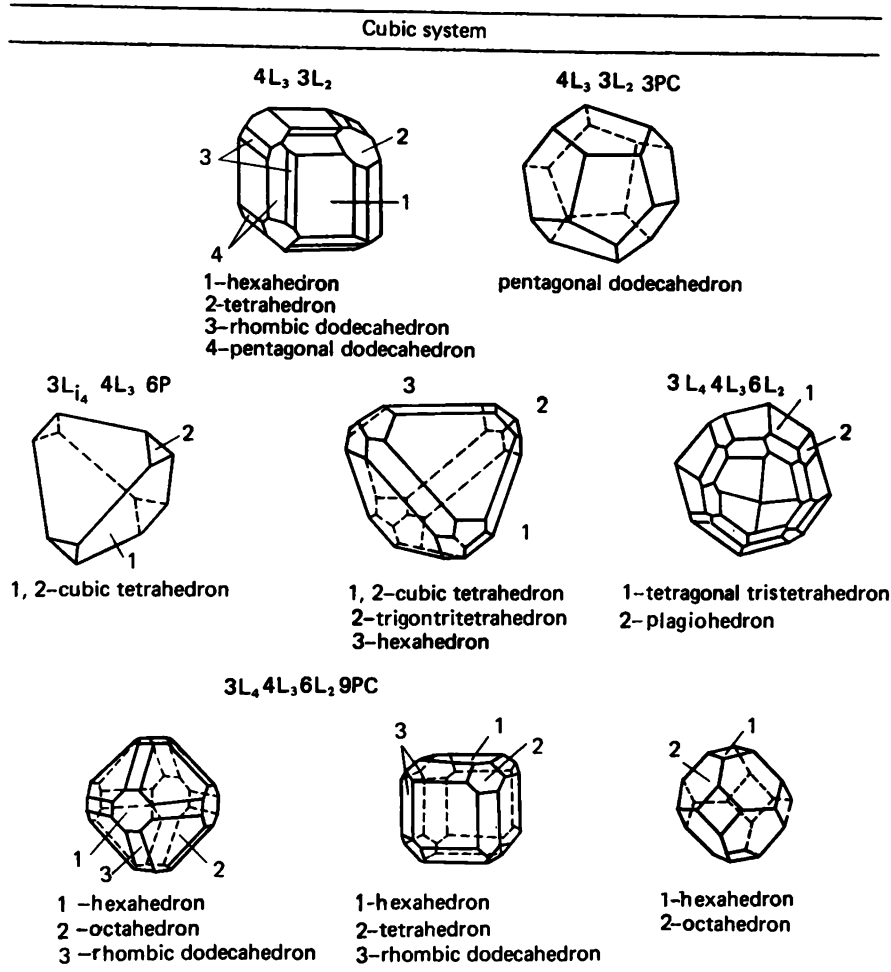
1–trigonal prism
2–pinacoid
3–trigonal dipyramid

$L_{i_6} 3L_2 3P$



1–pinacoid
2, 3–trigonal prism
4, 5–trigonal dipyramid

FIGURE 25. (*Continued*)



Regular growths are the growths of crystals along some particular crystallographical directions. They are called *twin crystals* and *triplet crystals* when two and three crystals are intergrown, and *polysynthetic twins* in the case of the intergrowing of a large number of crystals.

Irregular Growths of Crystals.Their main variety is exemplified by *druses*, or growths of more or less regular crystals growing on a single foundation (Fig. 27a). Their formation also presupposes open cavities, in which the free growth of crystals can take place. If within druses the crystals are approximately of the same size, are similarly oriented and are contiguous with each other, they are called *brushes*.

According to the quality of minerals taking part in their formation aggregates of mineral grains can be either monomineral, when they are formed by a single mineral, or *polymineral*, when several minerals participate in their formation.

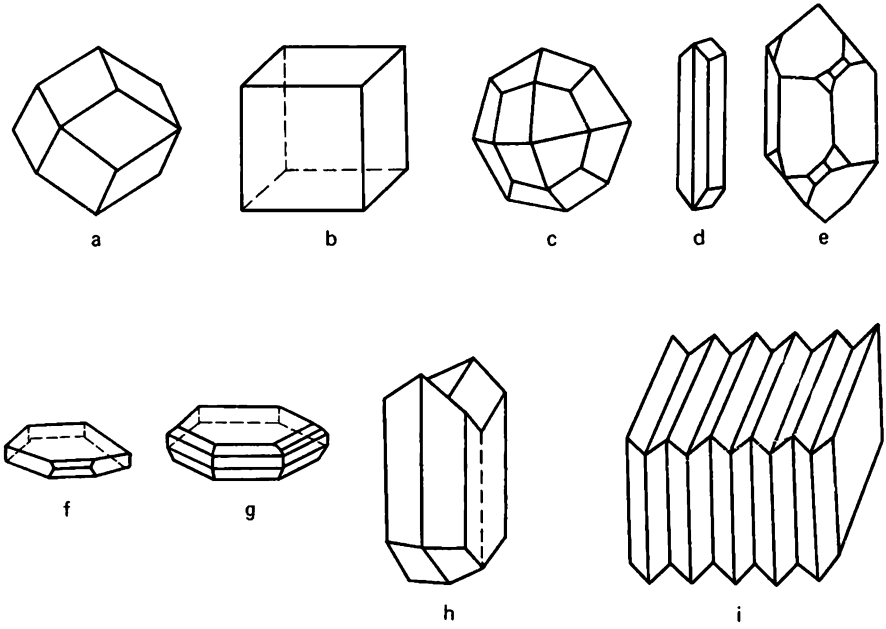
Granular aggregates are the most widespread form of mineralization in the earth's crust. They are formed in the course of a simultaneous crystallization of a large number of mineral grains from the solutions or melts. Due to reciprocal impediments in their growth the crystals in this case cannot have a regular form and acquire the form of the vacant space that was allotted to them.

According to the size of grains they are distinguished as either coarse- (more than 5 mm), medium- (from 5 to 1 mm) and fine-grained (less than 1 mm) aggregates. Depending on the form of grains granular aggregates can be prismatically granular, foliated, scale, acicular, rod-like, fibrous, etc.

Earthy and compact aggregates are those in which individual mineral grains are undistinguishable with the naked eye. In addition to this in earthy aggregates the cohesion between mineral particles is inconsiderable and they soil our hands. This kind of aggregates are mainly characteristic of exogenic processes of mineral formation.

Rounded aggregates include secretions, concretions and solites. *Secretions* (see Fig. 27*b*) are formed when the mineral substance fills the rounded voids in rocks. In addition to this, the mineral substance is deposited on the walls of the cavity and gradually fills it from the periphery to the centre. That is why secretions have

FIGURE 26. Monocrystals of various shapes and their regular growths:
a, b, c – isometric crystals; *d, e* – crystals elongated in one direction; *f, g* – crystals elongated in two directions; *h* gypsum twin; *i* polysynthetic twins



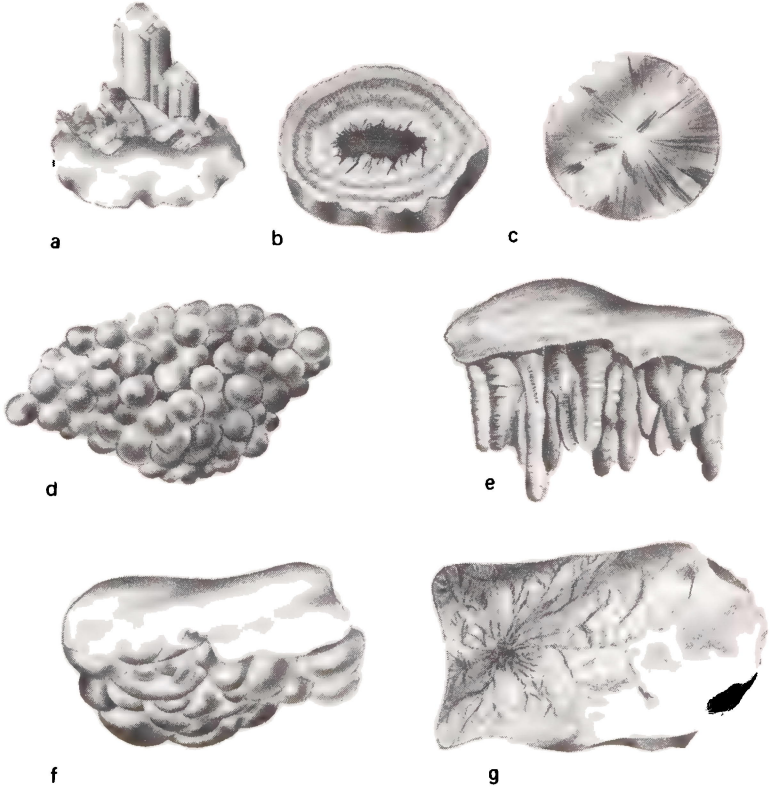
a concentrically zonal inner structure. In the centre of secretions there can remain cavities. Small secretions (up to 10 mm) are called *amygdules*, the larger ones are referred to as *geodes*.

Concretions (see Fig. 27*c*) represent septarian nodules of a rounded form, which form at the expense of the deposits of a mineral substance round some centre of crystallization. They are often characterized by a radiation structure. As distinct from secretions the growth of concretions goes from the centre towards the periphery.

Oölites are usually cemented aggregates of small (up to 10 mm in cross section) rounded varieties of concentric structure (see Fig. 27*d*). They are formed when the substance from some aqueous medium is mineralized. All rounded varieties are characteristic of minerals of exogenic origin.

Sinter aggregates are formed in voids (fissures, cavities, and caves) during the slow crystallization from the solutions that are, as a rule, colloidal, or in the course of their evaporation. They can be of various forms, viz. reniform (see Fig. 27*f*), botryoidal, irregular cylindrical (stalactites and stalagmites – see Fig. 27*e*), and in most cases their inner structure is concentrical.

FIGURE 27. Forms of mineralization



Thin films that cover the walls of fissures, the surface of rocks, are also called coatings, selvages, and blooms. They are most commonly formed during weathering processes. One of the varieties of thin films are *dendrites*. They originate during crystallization of minerals in thin fissures; their structure is arboreal and they look very much like the imprint of plants (see Fig. 27*g*).

Diagnostic Properties of Minerals

Every crystalline body possesses a complex of certain properties that are characteristic of itself. The most common properties employed for the visual identification of minerals are referred to as diagnostic properties, or features. They include: colour, streak colour of a mineral, lustre, hardness, cleavage, and others.

The Colour of Minerals.At present three colours of minerals are distinguished. They are: idiochromatic, allochromatic, and pseudochromatic.

The idiochromatic colour is conditioned by the crystallochemical characteristic features of the mineral itself. In most cases it is brought about by the inclusion into the composition of minerals of chromophores, or elements that are the carriers of colour. Chromophores comprise Ti, U, Cr, Mn, Fe, Co, Ni, and others. Depending on the valence condition these minerals have different shades of colour. Sometimes idiochromatic colour finds its expression as a result of the disruption of electrostatic homogeneity of crystalline structures.

Minerals with idiochromatic nature of colour always have a permanent colour, which considerably facilitates their diagnostics. This feature even accounts for the names that a large number of minerals have acquired: for instance, chlorite, ruby, hematite, albite, etc. Conversely, such terms as 'cinnabar' (carmine red), 'malachite green' entered our language as standard shades of colour.

The allochromatic colour is not in any way related to the crystallochemical nature of the mineral itself, but is associated with the foreign mechanical admixtures of certain shades of colour that are finely dispersed in it. The colour of a mineral is not constant in this case. For instance, the colourless quartz can acquire violet (amethyst), golden yellow (citrate), black (morion) and other shades of colour. If the dyeing pigment is not uniformly spread in a mineral, there emerges a variegated irregular colour, which is often found with agates, jaspers, and others.

The pseudochromatic, or false, colour is brought about by some optical effects– most often by the interference of the falling light during its reflextion from fissures, inclusions in minerals, and thin films on their surface. The case in point is the facing stone labradorite, composed of the feldspar of labrador. This phenomenon is known as iridescence.

Iridescent particoloured films are often discovered on slightly oxidized surfaces of chalcopyrite, bornite, and some other minerals. This is what is usually referred to as *tarnished surfaces.*

In all cases when it comes to the diagnostics of minerals we should aim at a more precise identification of their colour by comparing it with that of the commonly known objects, e. g. milk-white, straw-yellow, apple-green, etc.

The streak colour of a mineral on a dull porcelain plate or the colour of a mineral in powder can coincide with the mineral's own colour (with red cinnabar the streak is red, with black magnetite it is black), or be different from it (with brass yellow pyrite it is black, with steel grey hematite it is reddish brown, etc.).

It has been ascertained that there is every reason to determine streak colour of the opaque or semi-transparent brightly coloured minerals the hardness of which is less than that of the porcelain plate. For some of the minerals streak colour serves as a highly significant diagnostic feature. For instance, sphalerite is always characterized by a yellowish and brown streak, by which it is easy to distinguish it from galenite, the streak of which is black. Chromite differs from the minerals that resemble it by its greenish-grey streak. Hematite, linomite and magnetite, which often have the same colour when taken as a piece, easily lend themselves to be distinguished by their streak colour, which is reddish brown, yellow and black respectively.

The Lustre of Minerals.This characteristic is adequately objective diagnostic feature since it depends on the index of refraction as well as on that of reflection. The higher the refractive index of a mineral is the greater the intensity of lustre becomes. The former, in its turn, depends on the crystallochemical properties of the mineral and, primarily, on the density of its crystalline lattice.

The following basic types of lustre (in the ascending order of its intensity) are distinguished:

(1) *vitreous lustre*, which has very much in common with the lustre of glass, is characteristic of transparent and semi-transparent minerals the refraction index of which is 1.3-1.9 (fluorite, feldspars, carbonates, and others). It is the most widespread type of lustre shared by almost 70% of all minerals;

(2) *the adamantine lustre* is fairly strong and sparkling; it is characteristic of minerals with the refraction index 1.9-2.6 (diamond, sphalerite, cassiterite, zircon, etc.);

(3) *the semi-metallic lustre* has much in common with the tarnished surface of a metal; it is characteristic of semi-transparent minerals the refraction index of which is from 2.6 to 3.0 (cinnabar, hematite, graphite, and others);

(4) *the metallic lustre*, which reminds one of the lustre of a smooth surface of some metal, is characteristic of opaque minerals with the refraction index greater than 3.0 (pyrite, galenite, molybdenite, chalcopyrite, etc.). This group includes a large number of ore minerals that are of industrial value, and the names to which were originally given by the intensity of their lustre: e.g. lead lustre (galenite), antimonial lustre (antimonite), and others.

The lustre of minerals also depends on the character of the reflecting surface. If it differs from the ideally smooth one, the lustre, as a rule, is becoming more dull. Thus, there is *greasy lustre*, characteristic of nepheline, quartz and native sulphur on a new fracture; *waxy lustre* is typical of the surfaces with a rather coarse surface (silicon, talc). Finely dispersed (earthy) masses of minerals are characterized by *a dull lustre* (kaolin, limonite, pyrolusite). Aggregates with a parallel fibrous structure (asbestos, gypsum-selenite) are characterized by *silky lustre, the pearly lustre* is found to be typical of some of the tabular aggregates (muscovite, laminated gypsum).

Transparency. Minerals absorb, reflect and transmit the light that falls upon

them in differentways. According to this feature it is possible to classify them into *transparent*, or the ones that transmit the light perfectly well, and through which objects are seen very distinctly (rock crystal, Iceland spar); *semi-transparent*, through which we can see only the contours of objects; *translucent* minerals, which transmit the light only through a thin layer (feldspars, pyroxenes), and *opaque minerals*, those through which the light cannot pass at all (the absolute majority of sulphides, many oxides, and native metals).

Hardness. It is defined as the property of minerals, which enables them to resist the outer mechanical influence of a stronger body. In mineralogy relative hardness is usually defined by means of scratching one mineral with the other. For these purposes Mohs scale is employed. It comprises the following ten minerals arranged in the order in which hardness increases: talc–1, gypsum–2, calcite–3, fluorite–4, apatite–5, orthoclase–6, quartz–7, topas–8, corundum–9, and diamond–10.

Each mineral included in the scale of hardness scratches the preceding ones, while those that follow, or the harder ones, leave a small scratch upon it. In practice it is possible to approximately determine the hardness of a mineral with the help of such commonly known objects as a fingernail–2, a bronze coin–3.5-4, glass–5, the blade of a steel knife–6. According to hardness, minerals can be divided into three groups: *soft minerals*, that can be scratched by a fingernail (gypsum, talc, graphite); *minerals of medium hardness*, or *those that cannot be scratched* by a fingernail and do not leave any scratches on glass (carbonates, sulphates, chalcopyrite, galenite, and others); and *hard minerals* that scratch glass (quartz, feldspars, nepheline, arsenopyrite, cassiterite, etc.).

The exact determination of hardness is achieved with the help of sclerometers, or special instruments provided with an adamantine or metallic point.

Cleavage and Fracture. Cleavage is the ability of minerals to split or be dissected along definite crystallographic directions which results in the formation of even planes called *cleavage planes*. The latter are oriented parallel to the actual or possible faces of the crystal. This property is wholly dependent on the inner structure of minerals and finds its expression in those directions in which the cohesion forces between the material particles are of the least value.

The importance of cleavage as a diagnostic feature is most apparently illustrated by the fact that a number of minerals acquired their names in accordance with the degree of cleavage that is manifested in them. For instance, spars are minerals with good cleavage in several directions; orthoclase has cleavage at an angle of 90°, etc. Depending on the degree of perfection several types of cleavage are distinguished.

1. *Perfect cleavage*. The mineral is easily split into separate thin plates or leaves, and it is difficult to get the fracture in some other direction (micas, chlorides, talc).

2. *Good cleavage*. The mineral is easily split into cleavage planes, in addition to which the broken off fragments have very much in common with individual crystals (calcite, galenite, halite, fluorite).

3. *Distinct cleavage*. In the process of splitting cleavage planes, as well as uneven fractures in irregular directions, are formed (feldspars, hornblende).

4. *Imperfect cleavage*. Minerals are split in arbitrary directions which results

in the formation of uneven planes of fracture, and individual cleavage planes are found with difficulty (apatite, quartz, nepheline, cassiterite, native sulphur).

Sometimes none cleavage is also singled out. This is practically the same as the total absence of cleavage with minerals (magnetite, corundum, some varieties of natural metals). Cleavage can manifest itself in one or several (two, three, and less frequently – more) directions. There are quite a few cases when in one and the same mineral differently orientated cleavage planes have a dissimilar degree of perfection.

Cleavage can be established only in relatively coarse-grained formations of minerals. It is highly significant to distinguish cleavage planes from the faces of crystals; they are usually characterized by more prominent lustre and in contradistinction to crystal faces they lack striation.

In accordance with cleavage we discover fracture, i. e. a type of surface which is formed when the mineral is either broken or split. In the cases of good and perfect cleavage fractures are either plane, lamillar, or step-like. If cleavage is imperfect, the fracture is usually uneven; sometimes it is conchoidal with characteristic concave surfaces. It is typical of minerals of acicular and fibrous structure to have a splintery fracture (asbestos, hornblende); aggregates with a rough dull surface are characterized by an earthy fracture, when the surface of the mineral is covered, as it were, with a coating of dust (kaolinite, limonite).

Density. It primarily depends on the atomic mass or the ions that compose the crystalline lattice of minerals. A substantial role is allotted to the size of ionic radii, the increase of which compensates, as a rule, for the growth of atomic mass.

In macroscopic determination the density of minerals is approximately established by weighing the minerals on one's hand with such assessments as 'heavy', 'medium', or 'light'; in addition to this a comparison is often made with the samples of various minerals that are of similar size.

The density of minerals varies within the limits of 0.9 and 23. In this case minerals, having the density of up to 2.5 (sulphur, gypsum, halite, opal), belong to light minerals. Medium density (from 2.5 to 4) is shared by a very large number of minerals, such as quartz, feldspars, micas, and calcite. Heavy minerals have density greater than 4. In most cases they are ore minerals (pyrite, galenite, sphalerite, chalcopyrite and others). Of non-metallic minerals high density is shared by barite, which is its most important diagnostic feature.

Magnetization. There are not many minerals that have magnetic properties (magnetite, pyrrhotite) and, hence, this feature has a great diagnostic significance. Magnetization is discovered by the manner in which the mineral reacts to the magnetic needle of a compass.

The reaction with the diluted hydrochloric acid is employed for the diagnostics of minerals belonging to the class of carbonates. These minerals have a vitreous, less often dull lustre, medium hardness, good cleavage and relatively light colour. The intensity with which the reaction takes place is not the same for various carbonates.

Calcite boils rapidly in one piece with the emission of carbon dioxide bubbles; dolomite boils in powder; magnesite with cold hydrochloric acid reacts neither in one piece nor in powder; the reaction requires heating; siderite – in the reaction with heated hydrochloric acid yields a brown coating of ferrous chloride.

The solubility in water (taste) is characteristic of native chlorides. It serves to easily distinguish saline halite from bitter saline sylvite.

Other properties of minerals that are of diagnostic value include *radioactivity, luminescence* (the luminosity under the activity of ultraviolet radiation), *malleability, brittleness,* and others.

It should be mentioned that the properties of minerals are used not only for diagnostics, but also in various technological processes. Thus, for instance, the low solubility of salts has formed the basis for their recovery by means of subsurface leaching. Various degrees of density of ore and non-metallic minerals have laid the foundation for the gravitational methods of enrichment of mineral resources. The magnetic properties of minerals are widely used in processes of the enrichment of iron ore.

Classification of Minerals

The classification of minerals that is accepted in modern science is based on *the crystallochemical principle* (Table 5).

The singling out of major units of classification, viz. types and classes, is based on the chemical principle (the type of chemical compounding, the character of chemical bond and acid radicals). The division into subclasses is carried out according to the structural principle, i.e. by the character of structural motifs in the crystalline lattices of minerals.

A large number of minerals contained in the earth's crust are of great industrial value. Minerals can be used, firstly, for the extraction from them of

TABLE 5. Classification of Minerals

Types	Classes	Subclasses	Examples of minerals	Total number of minerals	Mass content in the earth's crust, %
I. Simple substances		Coordination	Brass, diamond	3.3	0.10
		Ring	Sulphur		
		Layer	Graphite		
II. Sulphur compounds and their analogues	Sulphides and their analogues	Coordination	Galenite, sphalerite, bornite, chalcopyrite, pyrite, pyrrhotite, pentlandite	13	1.15
		Island	Pyrite, arsenopyrite		
		Chain	Cinnabar, antimonite		
		Layer	Molybdenite		

TABLE 5. (*Continued*)

Types	Classes	Subclasses	Examples of minerals	Total number of minerals	Mass content in the earth's crust, %
III. Oxygen compounds	Oxides and hydroxides	Coordination	Uraninite		
		Chain	Cassiterite, psilomelane, pyrolusite, diaspore		
		Layer	Corundum, ilmenite, hematite, hydrargillite	12.5	17
		Framework	Cuprite		
	Silicates and alumosilicates	Island	Olivine, garnet, disthene, epidote		
		Ring	Beryl		
		Chain	Pyroxenes, amphiboles	25	75
		Layer	Micas, chlorites, talc, serpentine		
		Framework	Feldspars, nepheline, quartz		
	Carbonates	Island	Calcite, dolomite, magnesite, siderite, malachite	4.5	1.70
	Sulphates	Island	Anhydrite, barite	9.0	0.50
		Layer	Gypsum		
	Phosphates	Island	Apatite	17	0.70
	Wolframites and molybdates	Island	Wolframites, scheelite	1.0	0.15
	Other classes of oxygen compounds	—	—	9	3.2
IV. Halides	Chlorides	Coordination	Halite, sylvite		
		Island	Carnallite	5.7	0.50
	Fluorides	Coordination	Fluorite		

some valuable components; they are usually called ore minerals, e.g. galenite, sphalerite, chalcopyrite, wolframite, cassiterite, magnetite, apatite, etc.; secondly, owing to some of their important properties they can be made use of directly as minerals (mica, asbestos, precious stones and Iceland spar), and, lastly, there are many minerals that form rocks that often find practical application.

Paragenesis of Minerals

The study of the mineral composition of rocks and deposits of mineral resources have led the scientists to the idea that minerals are found in nature in particular groups, or form regular communities (associations) with each other. The idea of a certain regularity in discovering minerals together, which at first originated as a result of empirical generalizations of numerous facts accumulated in age-long mining and prospecting activity of people, for the first time found its scientific expression in the works of Academician V. Severgin, who in 1970, introduced in mineralogy the concept of the 'sequence' of minerals. In Europe it was proclaimed in 1849 by J. Breithaupt as 'paragenesis'. It has been firmly established in geological literature since.

Paragenesis can be defined as a common location of minerals conditioned by the common features pertaining to their origin. In this sense it is possible to speak of mineral associations of magmatic, sedimentary formations, associations of the weathering crust, etc. The specification of mineralogical investigations has enabled the scientists to distinguish paragenetic associations, characteristic of certain types of the deposits of mineral resources and even for individual types of mineral resources. For instance, chromite deposits of magmatic origin are properly characterized by the association of chromite and serpentine, the association of pyrrhotite, pentlandite, chalcopyrite, magnetite, the mineral of platinum and palladium are typical for sulphide copper and nickel deposits, the antimony and mercury deposits are found to be remarkable for the associations of cinnabar, antimonite, fluorite. etc.

Originally, the term 'paragenesis' referred only to minerals, but in 1909 V. Vernadsky spread it also to chemical elements, since the chemical and mineral composition of natural formations are closely interrelated. Thus, for instance, for the mineral deposits of salts it is possible to speak of the paragenetic association of minerals, viz. halite, sylvite, carnallite, gypsum, native sulphur and bitumens and the association of elements corresponding to it, Na, K, Ca, Mg, Cl, S, C, H, and O: for gold and sulphide ores the association of ore minerals comprises gold, arsenopyrite, grey ore, galenite, sphalerite, pyrite, and its corresponding association of elements includes Au, Cu, Fe, Pb, Zn, As, Bi, etc.

The analysis of paragenetic relationships of minerals is at present the key to the interpretation of any process of mineral formation. Besides, the study of paragenetic associations of minerals is of no minor importance for the more normal prospecting and exploration as well as for the commercial value of the deposits of mineral resources.

Rocks are the most widespread and stable forms of paragenetic associations of minerals whose general characteristic is given in the next chapter.

Chapter 6 Petrographic Composition of the Earth's Crust

General Information on Rocks and the Processes of Their Formation

Rocks represent the material medium which is called the earth's crust. Without knowing the conditions of rock formation, their composition and properties, it is impossible to conduct rationally any operations connected with the prospecting and exploration of deposits. The detailed study of rocks is the subject of such an independent geological science as *petrography*.

Rocks are defined as stable paragenetic associations of minerals, which emerge as a result of definite geological processes and that form independent bodies in the earth's crust in geology.

It should be mentioned that all artificial aggregates received as a result of the practical activity of man (cement, slags, ceramics, etc.) are not regarded as rocks.

Neither can it be justified to consider as rocks the recent sediments (e.g. the sands and clays in river beds and on seashores), which are no more than the products of unfinished geological processes that are still now in progress. Mineral associations entering into the composition of ore veins are usually not referred to rocks either.

The geological processes which lead to the formation of rocks are also called *processes of petrogenesis*. These processes are actually three in number:

(1) the crystallization of natural silicate melts (magmas or lavas), which come from the depths of the Earth; this process is known as magmatism;

(2) the destruction of previously existing rocks in surface conditions, the deposition of products of decomposition in different kinds of water basins and on the surface of land (sedimentation);

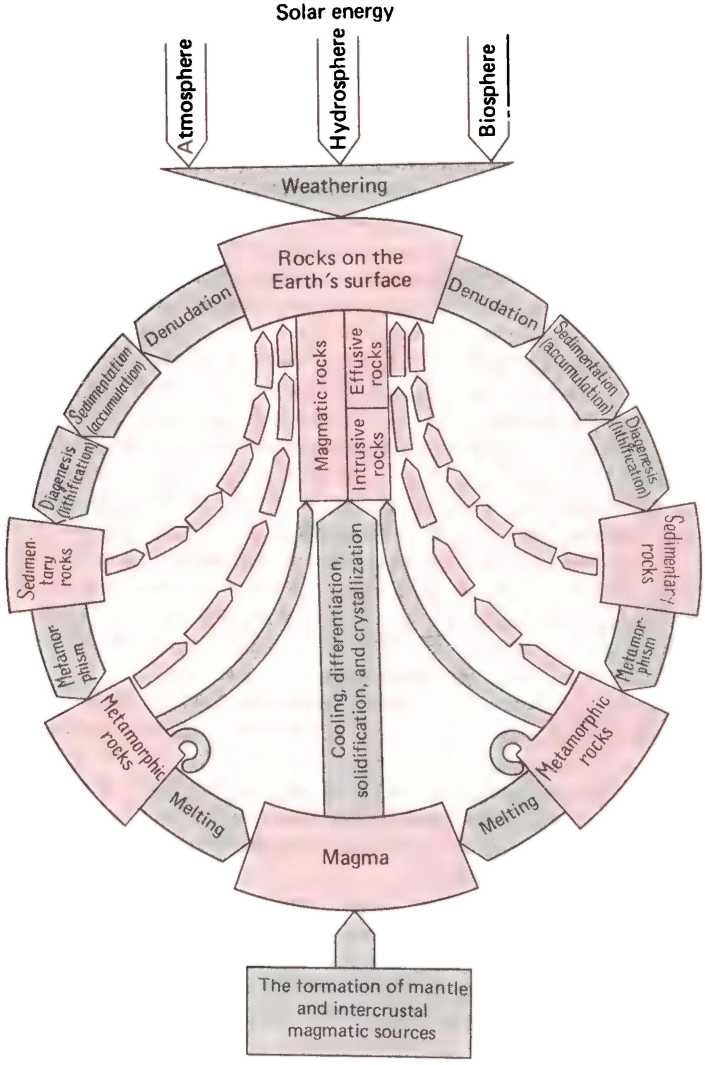
(3) the recrystallization of rocks of any origin as a result of the alteration of physicochemical conditions – the temperature rise and pressure (metamorphism).

The conditions of rock formation, determining their composition and outer appearance are usually referred to as facies conditions. In other words, facies can be defined as a homogeneous complex of rocks in terms of composition that were formed in similar conditions.

In accordance with three basic types of formation of rocks, all rocks composing the earth's crust are divided into three genetic groups, viz. magmatic, sedimentary, and metamorphic. In addition to this, only magmatic rocks are to a certain extent primary as far as their origin is concerned, since rocks belonging to the other genetic groups are no more than the result of certain transformations of the earlier existing rocks. In this connection it is quite clear why magmatic rocks are most widely spread: down to the depth of 16 km the earth's crust consists of 95% of magmatic rocks, the metamorphic and sedimentary rocks accounting for 5%. On the Earth's surface the relationship is somewhat different: sedimentary

rocks make approximately 70-75%, while magmatic and metamorphic rocks account for about 25-30%. The processes of building up various types of rocks that are interrelated, have a single rock-formation cycle (see Fig. 28).

FIGURE 28. **Rock-formation cycle (according to O. Cotes)**



Material Composition of Rocks. The Concept of Phase Composition

The material constituents of rocks of various genetic types can be: (1) mineral grains; (2) volcanic glass; (3) fragments of previously existing minerals and rocks; (4) organic remains; and (5) cosmic dust. However, the main component of a great number of rocks are beyond any doubt minerals.

Minerals that compose rocks (the rock-forming minerals) are divided according to their function in the composition into principal and minor ones.

Principal minerals are minerals the number of which is predominant in the composition of rocks and that determines their affinity with a particular species. For instance, quartz, orthoclase, acid plagioclases, and biotite are the principal minerals of granite, nepheline – nepheline-syenite, and others.

Though there are many minerals known to us in nature, the principal rock-forming minerals comprise only their inconsiderable number – 20-30 mineral species in all. Besides, among them there is a marked preponderance of those belonging to the class of silicates and allumosilicates, with carbonates, sulphates, chlorides and phosphates having a subsidiary role.

Minor, or as they are also called *accessory, minerals* enter into the composition of a rock in small numbers and do not determine its type of species. However, it is not infrequent that according to accessory minerals we single out individual varieties of rocks within the boundaries of a single species. Thus, granite, which in addition to biotite also contains muscovite, is called bimicaceous; granite, the composition of which has zircon as an accessory mineral, is referred to as zirconium granite, etc.

The principal minerals of some species of rocks can be minor in others. For instance, apatite, the main mineral of the apatite rocks of Khibiny tundras, where it is an industrial mineral, is found in a large number of rocks of the granite composition only as an accessory mineral.

The function of accessory minerals in the composition of a large number of rocks is also shared by ore minerals (chromite, magnetite, ilmenite, and pyrite), which, as a rule, do not form any concentrations in them, but are present in the form of dispersed impregnation.

Depending on the time of formation minerals, entering into the composition of rocks, are divided into primary and secondary varieties. *Primary minerals* are formed during the processes of formation of rock itself. *Secondary minerals* emerge in the later stage and at the expense of various processes of transformation of rocks as a result of changes that primary minerals undergo. In rocks of different origin one and the same minerals can be primary as well as secondary. For instance, carbonates in magmatic rocks are mostly secondary, whereas in rocks of sedimentary origin they are primary minerals, of which huge masses of limestones and dolomites are composed.

According to the number of minerals of which they consist rocks are divided into those that are *monomineral*, i.e. comprising only one mineral (quartzite, marble, labradorite and others) and the *polymineral* ones, consisting of several minerals (granite, diorite, gneiss, gabbro, etc.). In the earth's crust polymineral rocks are most widely spread.

Detailed mineralogical investigations of rocks are carried out by means of the microscopic study of their thin shears, or sections. A preliminary assessment of the mineral composition of rocks is rendered macroscopically, which is particularly important in field-work conditions.

The mineral composition of rocks is closely connected with the chemical composition of the latter, which is studied by means of methods employed in chemical analysis. It is usual that the results of analysis are expressed in the percentage of oxides of the main chemical elements entering into the composition of rocks (SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, CaO, Na_2O, K_2O, etc.). The indices of chemical properties are often used for the classification of various types of rocks.

The proper evaluation of physical properties of rocks and their massifs calls not only for the knowledge of their material composition, but also gives an idea of their *phase composition.* Rocks usually represent two- or three-phase systems and consist of interacting solid (mineral skeleton), liquid (pore solution), and gaseous phases. The phase equilibria in rocks are dynamic. They undergo constant disruptions as a result of the continuous migration of porous moisture and heat exchange in the Earth's geothermal field. The dynamism of interphase equilibria can serve as a mechanism for the change in the condition and properties of rocks.

The pore moisture in rocks is found to be in free and combined conditions. When the temperatures are negative water appears in its solid state, or ice. The pore water in a free state is distinguished by a high degree of mobility and chemical activity. These properties of the pore solutions are the ones that condition the exchange reactions, diffusion and other processes, including those that bring about changes in consistency, strength indices, and the stability of rocks. The presence of a free liquid phase also determines ionic electric conductivity, typical of most rocks.

The firmly combined water (adsorbed or hygroscopic water), which is found to be under the activity of the powerful forces of attraction of mineral particles to the surface, is distinguished from the free water by low values of dielectric constant and an inconsiderable dissolving ability. The combined water in rocks can continue its movement only under the action of osmotic pressure. The maximum content of adsorbed water characterizes the highest degree of hygroscopicity of rocks.

The gas phase covers from 1-12 to 40-50% of the volume of rocks. The gas components are predominantly found in adsorbed, dissolved, and free conditions. Adsorbed gases are retained on the surface of mineral particles by the forces of molecular attraction and form upon them polymolecular gas films. The content of adsorbed gases depends on the mineral composition of rocks, the degree of their dispersion, humidity, temperature, pressure, the content of organic substances and the content of gases themselves. With the growth of adsorbtional properties minerals give rise to the following series: quartz, muscovite, biotite, calcite, limonite, koalinite, and hydromicas.

A part of gases in pore moisture is found in a dissolved state. They are mainly represented by oxygen, carbon dioxide, nitrogen and others. The presence of dissolved gases activates leaching, hydrolysis, oxidation, and other weathering

processes of rocks and causes corresponding alterations in their composition and properties. Free gases fill the pore space of a rock not occupied by water and make up the fundamental mass of the gaseous phase of rocks.

Fabric of Rocks

The fabric of rocks, in the opinion of some researchers, is a multilateral concept, involving the structure of the mineral skeleton, the pore space, and the character of structural bonds existing between the constituent rocks.

The fabric of the mineral skeleton of rocks is characterized by texture and structure. *Texture* is defined as the totality of features of rocks, conditioned by the degree of crystallinity, absolute and relative dimensions, form, mutual arrangement, and the way mineral components are combined. The morphological units of texture are mineral grains, fragmental (clastic) material, uncrystallized glass, etc.

According to the degree of crystallinity (in magmatic rocks) the textures are distinguished as *holocrystalline* and *non-holocrystalline* ones. Depending on the size of grains textures can be either *equigranular*, if the grains entering into the composition of rocks are approximately of the same dimensions, or *non-equigranular*. As far as the absolute size of mineral grains is concerned it becomes possible to single out *coarse-*, *medium-*, and *fine-grained textures*.

Forms of grains and their interrelations are characterized by the correspondence to the crystallographic shape of a mineral. In accordance with this feature mineral grains are classified as *idiomorphic*, when the mineral grains are regularly faceted and have crystallographic contours typical of them, and *xenomorphic*. The latter group can be exemplified by mineral grains of irregular shapes, the form of which is determined by the faces of neighbouring crystals. The degree of idiomorphism depends on the conditions of crystallization, as well as on the crystalline property of minerals. Some of the rocks are characterized by reciprocal intergrowths of mineral grains which help to maintain the enhanced degree of stability (pegmatites).

Structure is determined by the orientation, relative arrangement, and the means of filling the space by the mineral masses of a rock, which characterize the degree of its homogeneity and continuity. The morphological units of structure are combinations of mineral grains, or mineral aggregates.

Depending on the character in which the mineral grains are arranged, the degree of regularity in their arrangement structures are regarded as either *homogeneous* or *heterogeneous*. The latter are divided into those that are *bedded, foliated, eutraxitic* or *banded, veined, mottled*, etc. According to the density of the packing, mineral grains in the volume of rock structures are treated as *dense*, or *massive, porous, vesicular*, etc. In numerical values this particular index of the structure can be characterized by the values of porosity, coefficient of porosity, and the density of rock.

The construction of pore space is determined by the morphological characteristic features of voids (pores), i.e. their size, form and spatial relationships. According to the type of formation of original interstice that emerged when the

rock was being formed itself (e. g. intergranular and intermineral varieties of porosity found in most of the rocks) is distinguished from the secondary type of interstice which originated in the process of secondary alternation of rocks or in the course of tectonic deformations (jointing, void of leaching, etc.).

The size of voids is characterized by the diameter of the pores and the extent to which fissures are exposed. This makes it possible to single out megapores (cavities), the volume of which can reach several cubic metres: macropores with the diameter more than 0.1 mm and micropores the diameter of which is less than 0.1 mm (P. Panyukov). The latter fall into capillary (0.002-0.1 mm) and subcapillary (less than 0.002 mm) ones. According to the degree of opening fissures can be of supercapillary (with the exposure greater than 0.25 mm), capillary (0.001-0.25 mm) and subcapillary varieties (less than 0.001 mm).

Pores are said to be closed, if there is no connection between themselves and the environment. In those cases when this kind of connection exists, pores are defined as open. The distribution of voids in nature can be either regular or irregular. In the course of time the pores in rocks can either be increased, decreased, or remain without any changes. That is why in the petrographic characteristic of rocks, conducted with the aim of evaluating the physical properties, the study of the time changes of voidance is considered to be quite essential.

The nature and what lies behind the formation of structural bonds between the minerals of which the rocks are composed have not yet been fully discovered. In modern petrophysics (the science of the physical properties of rocks) it is considered that the intermineral bonds in rocks are accomplished by means of surface and volumetric forces.

The nature of surface forces is the following. The atoms in a crystalline lattice experience considerable forces of attraction of the atoms that are contained in the mineral's body. In the surface layer these forces are not compensated for from the outside, as a result of which the surface layers of mineral grains possess an excess energy, known as surface energy. It is a part of this energy that is expended on the formation of intermineral bonds. The extent to which the surface energy is realized in the energy of intermineral bonds is directly proportional to the specific surface of mineral grains and inversely proportional to the distance between them.

It is, therefore, apparent that the most stable and firm bonds are established at the direct contact between the mineral constituents (volume forces). These forces are the most characteristic of magmatic and metamorphic rocks. They have crystalline nature, i. e. they are established in the process of crystallization (or recrystallization) of rocks.

When the distance between mineral grains is remote, the intermineral bonds become weaker, by their physicochemical nature they acquire case-hardening properties, which are typical of the greater number of sedimentary rocks, or water and colloidal ones, which are characteristic of rocks belonging to the argillaceous type. Lastly, in loose sedimentary rocks (sands, pebble-bends, etc.) the interaction between the fragments is carried out by means of forces of friction, i. e. the structural bonds acquire a mechanical character. The character and nature of structural bonds, as well as other features of rock structure, play the

main role in the formation of their physical properties, the knowledge of which is absolutely essential for the appropriate carrying out of mining and technological operations.

Forms of Attitude of Rocks. A Concept of Formations

Another significant feature of rocks usually studied in natural (field-work) conditions is *the form of their attitude*. The latter is apprehended as forms of geological bodies formed by them in the earth's crust. The knowledge of such forms is of great theoretical and practical value. Geological bodies composed of rocks are their complexes and deposits of mineral resources or the medium enclosing them. The combination of forms of attitude at a given particular part of the territory determines the geological structure of the rock massif, the features of the spatial distribution of its properties, hydrogeological and geological and engineering conditions. Hence, the forms of attitude have a marked impact on the character and intensity of the physical processes that take place in the natural or disturbed by mining operations of rock massif.

The forms of rock attitude are divided into *primary* (undisturbed) – those that originated at the same time with the formation of the rock itself, and *secondary* (disturbed), or those that emerged as a result of the dislocation of primary forms.

In the earth's crust rocks as well as minerals give rise to certain communities known as *geological formations*. N. Shatsky has defined the formations as natural complexes, communities or associations of rocks, the individual parts of which are in close paragenetic ties with each other as far as their age and spatial relationships are concerned. The formations can be singled out according to the origin of rocks (magmatic, sedimentary, and metamorphic), their petrographic composition (halogenous, carbonaceous), predominantly developed in various structural elements of the earth's crust (geosynclinal, platform), as well as by some other features.

Chapter 7 The Age of Rocks (Geological Chronology)

Main Stages in the Evolution of the Earth

The chronology of events in the history of the Earth, its age, as well as the history of the development and age of the earth's crust, or the geosphere, within the confines of which the main activity of man is concentrated, are the subjects with which the scientists are immediately concerned, since all these problems have a theoretical and practical importance.

At present two large stages (unequal in their duration) are distinguished in the formation and development of the Earth. They are the pregeological and geological stages.

The pregeological stage, also known as *the cosmic* or *planetary* stage, covers the span of time from the moment the Earth emerged as a planet to the time when the formation of the earth's crust began. Its history cannot be reconstructed with the

help of geological methods and our knowledge about this stage is based on the general concepts pertaining to the development of the Earth as one of the planets of the Solar system.

What lay at the bottom of the pregeological evolution of the Earth was the stratifying of the originally homogeneous substance into spheres, or geospheres, which resulted in the formation of the solid body of the Earth, the atmosphere and the geosphere.

The stratification went parallel with the progressive consolidation (contraction) of the primary condensation, the consolidation resulted in the heating of the substance, which became even greater at the expense of the radioactive processes. In its turn the rise in temperature activised the processes involving the differentiation of the substance. The emission of gases contained in the original substance of the Earth, led to the formation of the primary atmosphere.

The content of the primary atmosphere presumably had a prevalence of carbon dioxide and water vapours which accounted for the fact that it was practically impenetrable for the Sun's rays, and the heating of the Earth's surface was taking place only at the expense of the inner heat. In the lower layers of the atmosphere, adjacent to the Earth's surface, isothermal conditions were formed, as a result of which hydrometeorological processes were almost totally absent. When the processes of consolidation and differentiation of the Earth's substance were in the main completed, the Earth's surface together with the atmosphere began to cool. This resulted in the condensation of water vapours, the formation of hydrosphere and the increase of transparency of the atmosphere. In connection with the irregular heating of the Earth's surface by the Sun, the water and air masses came into motion, and there appeared a general planetary process of atmohydrocirculation, which is the motive force of exogenic processes. The moment exogenic processes came into being the Earth entered a new, geological stage in its development.

The geological stage covers the time from the formation of the earth's crust until now, when the Earth has already become remarkable for the two main groups of processes – the endogenic and exogenic ones.

With the emergence of exogenic processes the Earth's surface became the field within which there began to develop the processes of disruption, the transportation of disrupted products and the formation of masses of sedimentary rocks. The unity, in which exogenic and endogenic processes function, give rise to the consequent transformations of sedimentary rocks, i. e. to the phenomena of metamorphism, the formation of magma, volcanism, which gradually and unceasingly make the structure of the earth's crust more complicated. This results in the formation of the highly intricate and heterogeneous in its composition earth's crust of the present-day shape.

The complicated, many-stage process in the development of the earth's crust is reconstructed by means of investigating the geological data that have been preserved from this process. This includes the substance of the earth's crust, i. e. the minerals and rocks entering into its composition; geological bodies, or forms of position of mineral masses; structural forms of various orders, formed by geological bodies: remnants of animal and plant organisms, buried in the mineral masses of the earth's crust.

In order to analyze the highly complicated combination of rocks and structural forms of the earth's crust and get from all this the information essential for practical purposes, it is necessary to know how to determine the sequence in the formation of geological objects, primarily rocks, that compose the earth's crust.

Relative Age of Rocks and Methods of Determining It

The relative age determines the sequence of geological formations, in particular, rocks in the course of geological development. Among the methods of determining the relative age *geological, stratigraphic* and *biostratigraphic methods* are distinguished.

The first group includes stratigraphic and mineralogical and petrographic methods.

The stratigraphic method is based on the investigation of the sequential deposition of sedimentary rocks. Its main rule consists in that within the undisturbed masses of rocks the overlapping layers are always younger than the underlying ones. If in geological sections we find crossing bodies of magmatic rocks, then the rule works: the crossing body is younger than those it intersects. Thus, in Fig. 29 the crossing body α is younger than beds *B* and *C*, but much older than bed *A*. The crossing body β is found to be the youngest since it intersects all the beds and body α. The main drawback of this method consists in that its application makes it difficult to compare rocks that are situated at a considerable distance from each other, which also concerns rocks the bedding of which is complicated by tectonic dislocations.

The mineralogical and petrographic method is founded on the determination of relative age by means of contrast and correlating individual layers of rocks according to the characteristic features of their composition and structure. However, this method of parallelization of layers is applicable only at nearly situated points and proves to be unreliable in geological sections remotely situated from each other. It has been established that in a large number of cases rocks of the same age are characterized by quite different composition, and, conversely, the composition of coeval layers can be quite different according to

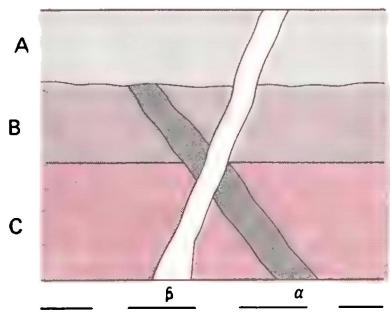


FIGURE 29. The stratigraphic method used in determining the relative age of rocks (the explanations are given in the text)

petrographic composition, which shows the distinction in the conditions under which they were formed.

The biostratigraphic paleontological methods are the ones that are most reliable in determining the relative age of rocks. They are based on the investigation of the remains of animal and plant organisms that existed in the previous geological epochs and were buried in the masses of sedimentary rocks. What is best preserved includes hard skeletal parts of organisms (shells, armours, and bones), that are partly or wholly replaced by mineral formations, in most cases by silica and calcite.

What lies at the bottom of these methods is the basic principle of the theory of evolution concerning the consecutive change in time of non-recurrent complexes of flora and fauna. In the course of geological history the organic life has been developing gradually – from the simplest primitive forms, the remnants of which are usually confined within the most ancient rocks, composing the earth's crust, to the highly organized organisms that correspond in time to the most recent depositions.

Every period of geological history is characterized by its own complex of flora and fauna forms. However, by far not all the organisms are of equal importance when it comes to establishing the age of rocks.

The main role among them belongs to the so-called leading fossils. Their characteristic features comprise: (1) rapid evolution in time and, consequently, restricted vertical occurrence in geological sections; some of the animal species have survived over millions of years of geological development without undergoing any substantial changes, and their remains are now found in the most varied layers of rocks of different age; the remains of this kind cannot possibly function as leading fossils; (2) a wide spreading in area, as well as the abundance of specimens and their adequate state of preservation.

Among the biostratigraphic methods an important role is attributed to *the micropaleontological method*, which is based on the analysis of microorganisms, and primarily the simplest ones, as well as to *the spore and pollen analysis*, which is concerned with the investigation of microscopic remains of plants: viz. spore vessels of sporophytes and grains of pollen of seed-bearing plants. These vegetable formations are composed of extremely stable substance and are thus well preserved in a fossil state. It should be mentioned that paleontological methods cannot be regarded as universal either, and that is why in determining the age it often becomes necessary to employ a whole range of methods, even in the case of which there exist masses in the geological formations of the earth's crust the age of which has either been approximately determined or not established at all.

In studying the earth's crust geologists elaborated the periodization of its history and created *the stratigraphic* and its corresponding *geochronological scales* that are universal for the whole world.

The terms employed to designate the stratigraphic and geochronological units are internationally accepted. They were confirmed at the second and the third sessions of the International Geological Congress in 1881 and 1900. In what follows we have stratigraphic and related to them geochronological subdivisions:

Stratigraphic	*Geochronological*
Eonothem	Eon
Group (Erathem)	Era
System	Period
Series	Epoch
Stage	Age

Stratigraphic subdivisions are used for the designation of complexes of layers of rocks, while their corresponding geochronological subdivisions indicate the time during which these complexes of layers were accumulated.

Eonothems are the largest stratigraphic subdivisions the formation of which took place within several geological eras. At present two eonothems are distinguished: Phanerozoic, uniting Paleozoic, Mesozoic, and Cenozoic groups and Cryptozoic which brings together Proterozoic and Archean groups.

Groups are large subdivisions of the stratigraphic scale. They are complexes of deposits that were formed in the course of a single era. They cover large periods in the development of the earth's crust. Group boundaries correspond to the critical landmarks in the history of organic world. This found its expression in the names given to these groups: e. g. Archean, Proterozoic, Paleozoic, Mesozoic, and Cenozoic.

The groups are further divided into *systems*, which cover the deposits that were formed during one period and which are usually distinguished by families and orders of organic forms. The names of the systems are, as a rule, connected with the names of those places where the corresponding deposits were first established and described, or, on the other hand, by the composition of prevailing rocks. Thus, for instance, the Devonian system acquired its name after the county of Devonshire in England, the Permian system is associated with the Perm region, where these deposits are widely spread, the Carboniferous system reflects the comprehensive development of coal, the Cretaceous system is connected with the areas where chalk is found in abundance, etc. Still smaller subdivisions include *series* and *stages.*

In addition to the international scale auxiliary local stratigraphic subdivisions are also widely employed. They comprise *groups, suites*, and *members.*

On geological maps rocks of various age have their own generally accepted colours and are designated with definite indices.

Absolute Age of Rocks and the Methods of Determining It

In a large number of cases for the solution of problems in theoretical and practical geology it is not sufficient to determine only the relative age of rocks. It is also necessary to establish their absolute age, expressed in commonly employed units of time.

As is known from historical facts geological methods were the first ones that were used to meet these purposes. *Geological methods* are highly varied, but most of them are based on the study of the rate of various geological processes and are founded on the prerequisite that the rate is constant in terms of time.

TABLE 6. The Geochronological (Stratigraphic) Scale

Eon (eonothem)	Era (group)	Period (system)	Epoch (series)
	Cenozoic KZ	Quaternary Q	Holocene (Recent), Q_4
			Late Quaternary (Upper), Q_3
			Middle Quaternary (Mid), Q_2
			Early Quaternary (Lower), Q_1
		Neogene N	Pliocene (Upper), N_2
			Miocene (Lower), N_1
		Paleogene ℙ	Oligocene (Upper), P_3
			Eocene (Mid), P_2
			Paleocene (Lower), P_1
Phanerozoic	Mesozoic MZ	Cretaceous K	Late Cretaceous (Upper), K_2
			Early Cretaceous (Lower), K_1
		Jurassic J	Late Jurassic (Upper), J_3
			Middle Jurassic (Mid), J_2
			Early Jurassic (Lower), J_1
		Triassic T	Late Triassic (Upper), T_3
			Middle Triassic (Mid), T_2
			Early Triassic (Lower), T_1
	Paleozoic PZ	Permian P	Late Permian (Upper), P_2
			Early Permian (Lower), P_1
		Carboniferous C	Late Carboniferous (Upper), C_3
			Middle Carboniferous (Mid), C_2
			Early Carboniferous (Lower), C_1
		Devonian D	Late Devonian (Upper), D_3
			Middle Devonian (Mid), D_2
			Lower Devonian (Lower), D_1
		Silurian S	Late Silurian (Upper), S_2
			Early Silurian (Lower), S_1
		Ordovician O	Late Ordovician (Upper), O_3
			Middle Ordovician (Mid), O_2
			Early Ordovician (Lower), O_1
		Cambrian ϵ	Late Cambrian (Upper), ϵ_3
			Middle Cambrian (Mid), ϵ_2
			Lower Cambrian (Lower), ϵ_1
Cryptozoic	Proterozoic PR	Late Proterozoic, PR_2	
		Vend, V	
		Riphean, R	
		Early Proterozoic, PR_1	
	Archean AR		

Colour on the map	Age, mln of years	Organic world
Greyish-yellow	1.8	The growth of contemporary animal and vegetative world
Lemon-yellow	23 ± 1	The blossoming of angiosperms. The emergence of mammalian forms with many features common with the present-day ones. The evolution of the anthropoid ape. The invertebrates include gastropods and bivalves
Bright yellow	65 ± 3	The development of angiosperms. The rapid growth of primitive mammals. The invertebrates comprise foraminifera, gastropods and bivalves
Light green	130 ± 5	The appearance of angiosperms. The extinction of reptiles, ammonites and belemnites in the second half of the period
Dark blue	204 ± 5	Coniferous, cycad and ginkgoaceous plants. The flourishing of reptiles, inhabiting the waters, the earth and the air. The emergence of birds. Ammonites and lemnites are characteristic of the invertebrates
Lilac	245 ± 10	The growth of coniferous, ginkgoaceous and cycad plants. The appearance of mammals. A wide development of ammonoids and belemnites
Orange-brown	290 ± 10	The appearance and growth of coniferous and cycad plants. The development of reptiles. Invertebrates are represented by ammonoids and brachiopods
Grey	360 ± 10	Luxuriant arboreal vegetation (horsetail, lycopods). The development of amphibians. The appearance of insects. From invertebrates brachiopods, foraminifera, corals and echinoderms are appeared
Brown	400 ± 10	The appearance of ancestors of ferns. The flourishing of armoured fishes. The appearance of amphibian stegocephalians. Brachiopods and corals are the most developed ones among the invertebrates
Brownish-green	418 ± 15	Further growth of psilophytes
Dark green	495 ± 20	The appearance of armoured fishes. A wide development of invertebrates, e. g. trilobites, graptolites, cephalopods, brachiopods, and the development of corals and bryozoans
Bluish-green	570 ± 10	The emergence of the simplest land plants, or philophytes. The development of algae and bacteria. The invertebrates include trilobites and archaeocyatheans
Pink	670 ± 20 2600 ± 100	Algae and bacteria. Remnants of invertebrates in a poor state of preservation
Crimson pink	4500 ± 100	Traces of primitive organic forms

Thus, for instance, the age of the earth's crust was estimated by the overall thickness of marine sedimentary rocks. The said evaluation rests upon the postulate of the constant velocity of sedimentation, which is 1 m per 7 thousand years. The so-called *salt method* was based on the assumption that all the salts of the World Ocean emerged at the expense of salts that were brought by the waters from land and the annual supply of salts had not undergone any changes with time. However, the rate at which the accumulation of salt, marine sedimentation and other geological processes take place is in fact subject to changes in time.

Thus, all geological methods are far from being accurate and do not provide any reliable ground for the compilation of an absolute scale of geological time. A cardinal solution of the problem related to geological chronology became possible in the twentieth century in connection with the use for these purposes of radioactive elements that are contained in minerals and rocks.

The idea of employing *radiological methods* for establishing the absolute age of geological formations was first expressed by P. Curie in 1903.

All radiological methods are based on the phenomenon of spontaneous decay of radioactive elements and are derived from the prerequisite that the velocity of this process (the period of semi-decay) for each radioactive element is a constant value. Modern concepts in physics substantiated by experimental data enable us to consider that the velocity of radioactive decay within the span of geological time remains practically the same. Obviously, in each mineral containing a certain radioactive element, the process of decay is synchronous with the formation of the given mineral. It follows then that taking into account the known velocity of decay and knowing the content of the element and the products of its decay in the mineral under analysis, it becomes possible to determine its age.

At present a whole range of radiological methods for establishing the absolute age of rocks has been elaborated. Those that are the main ones are given below:

1. *The uranium-thorium-lead method* is based on the transformations of uranium into thorium which result in the formation of radiogenic lead: $^{238}U \rightarrow {}^{206}Pb + 8He^{4+}$, $^{235}U \rightarrow {}^{207}Pb + 7He^{4+}$, $^{232}Th \rightarrow {}^{208}Pb + 6He^{4+}$. The isotopic composition of lead and other radioactive elements is determined with the help of special devices called mass spectrometers. The uranium-thorium method is fairly reliable, though minerals that could be used for the analysis are relatively rare. Besides, one has to take into consideration the possibility that they may be found to contain lead of non-radiogenic origin.

2. *The potassium-argon method* is regarded as more universal since potassium refers to the elements of the earth's crust that are widely spread and yields a large number of minerals. It is based on that the isotope of potassium with the atomic mass 40 as a result of the capture by the nucleus of the electron from the closest to it K-level is transformed into argon $^{40}K + e \rightarrow {}^{40}Ar$. The age of the corresponding mineral formations is usually determined by the value of the ratio $^{40}Ar/^{40}K$. The greater this ratio is, the more ancient is the object that is determined.

3. *The rubidium-strontium method* is based on the transformation of the isotope of rubidium with the atomic mass 87 into strontium with the same atomic number. It is employed to determine the absolute age of micas that are

widely spread in the composition of magmatic and metamorphic rocks and some other silicates.

4. *Carbon dating* is a method which is used when it is required to establish the age of the younger (Quaternary) deposits as well as in archaeology. This is connected with the fact that the period of half-decay of the radioactive isotope of carbon ^{14}C, upon the transformations of which this method is based, comprises only 5.5-6 thousand years, which helps to determine only the age of such rocks, the time of the formation of which is not greater than 50-70 thousand years. Radioactive isotope ^{14}C is formed in the atmosphere under the influence of cosmic rays, it is well assimilated by the plants and is transformed into the composition of rock in their extinction.

The application of radiological methods has made it possible to establish the absolute age of a large number of ancient rocks of the earth's crust and come to the conclusion that the formation of the earth's crust began 3.6-4.5 bln years ago. It should, however, be mentioned that on all the continents of our planet rocks have been discovered the age of which varies from 3.8 to 3.6 bln years. Meanwhile, the age of the ancient rocks on the Moon reaches 4.5 bln years. If we admit the affinity of the processes of the formation of planets belonging to the terrestrial group, we shall have to state that rocks the age of which is between 4.5 and 3.8 bln years have not yet been found on Earth. They may be either situated in the depths that are not yet accessible for study, or have been reworked by subsequent geological processes. The Earth's age as a planet is estimated to be 4.5-5 bln years.

Radiological methods have made it possible to express in years the duration of the largest periods in the history of the earth's crust. The geological time-scale elaborated on the basis of the methods of relative and absolute geochronology is given in Table 6.

The absolute age of the Precambrian subdivisions is presented according to B. Sokolov's data. Those pertaining to Paleozoic, Mesozoic, and Cenozoic periods are in compliance with the ones received by J. Oden.

III Endogenic Geological Processes

Endogenic geological processes may well be regarded as of the first importance in the life of the Earth. They give rise to the fundamental forms of the relief of the Earth's surface, condition the manifestation of exogenic processes and, what is most significant, determine the structure of the Earth's crust as that of the Earth as a whole.

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Depending on the source of energy, conditions, and characteristic features of the development all geological processes are usually divided into two large groups, viz. the endogenic and exogenic ones.

To a certain extent this division is conventional, since these groups are inseparably connected with each other, interdependent, and thus reflect the variety, complexity and unity of all those forces that influence the Earth. It is precisely this organic harmony that comprises the nature of the process of self-development of the world and the essence of the geological form of matter motion.

Endogenic geological processes include: *tectonic movements of the earth's crust, earthquakes* as a special form of manifestation of recent dislocations associated with tectonic movements, *magmatism*, and *metamorphism*.

All endogenic processes, being the result of the interaction of the inner shells of the Earth, are generated or take place in the depths of our planet, i. e. within the earth's crust or the mantle, and are, consequently, developed in conditions of high temperatures and pressures.

The mineral systems generated by endogenic processes are, as a rule, distinguished by a lower energetic level than those that are original. Hence, endogenic transformations of substance occur mainly with the emission of heat according to the exothermal scheme. This is so not only with the process of formation of magmatic melts and their crystallization, but also with metamorphism and tectonic processes.

Most of the endogenic processes are directed towards the homogenization of the earth's crust substance. This particular trend is conditioned by the development of endogenic processes (high temperatures and pressure), in which the homogenization of various substances is most considerably enhanced. The highest degree of the miscibility of components takes place in natural magmatic melts.

All endogenic processes are most closely interrelated. Thus, tectonic movements are known to be one of the main reasons of the metamorphism of rocks. The same movements, which often disrupt the continuity of the earth's crust, become responsible for the formation of zones characterized by low pressure, which, in its turn, favours the emergence of the sources of molten magma. In the extreme forms of their manifestation (ultrametamorphism) metamorphic processes are accompanied by the remelting of substances, and, consequently, by the formation of sources of molten magma. The said interrelations and interdependence of various geological processes should never be left unheeded so that

one could always be in a position to reconstruct the most complicated image of the earth's crust development.

The question concerning the nature of those forces that are behind the endogenic processes is one of the most difficult not only in geology, but in natural sciences as a whole. There can hardly be any doubt that these forces are generated as a result of the most complex processes associated with the autonomous development of out planet, though which of them are predominant sources of energy has not yet been solved.

Chapter 8 Tectonic Movements of the Earth's Crust

Various dislocations of the original occurrence of rocks as well as changes in the elevation marks of the territory testify to the fact that since the time of its formation the earth's crust has been in a continuous state of motion. The mechanical displacements of matter connected with the development of the earth's crust and the deep shells of our planet are called *tectonic movements.* Eventually they give rise to an observable structure of the earth's crust and can therefore be regarded as creative movements. As in the case of most of the other endogenic geological processes tectonic movements are practically inaccessible to direct investigation. They can only be discussed by the results of their manifestations taking place in the structure of the earth's crust or the relief of the Earth's surface. For instance, in those areas that have been undergoing continuous subsidence we find accumulations of thick masses of rock. The parts of the territory characterized by the alternation of uplift and subsidence are found to be remarkable for the fall-out of individual layers from the section, etc.

Tectonic movements are allotted a special place among geological processes, since in a large number of cases it is precisely they that are the initial cause giving rise to numerous consequences that find their expression in other geological processes. A comprehensive study of tectonic movements is undertaken by geotectonics – a science dealing with the structure, movements, deformations, and development of the earth's crust and the upper mantle (tectonosphere) connected with the development of the Earth as a whole. Structure can be defined as heterogeneity in the distribution and conditions of the occurrence of rocks belonging to various types of composition. Deformations are understood as a process which leads to disturbance, or dislocations in the original occurrence of rocks.

Tectonic movements are exceptionally diverse as far as the forms of their manifestation in time and space are concerned, and that is why it is more complicated to classify them. In recent years, according to various features a number of classifications of tectonic movements have been suggested. We have a brief account of classifications that were put forward by the Soviet scientists V. Beloussov and V. Khain.

V. Beloussov's classification is based on the division of tectonic movements according to the scale and character of their manifestation, and the scope of rocks covered by them. Tectonic movements are divided into intracrustal ones, or those that are spread over individual formations of the earth's crust, and the

total crustal (deep) movements, that are manifested in the dislocations of the crust as a whole. In their turn, the intracrustal movements are further subdivided into folding and fault varieties, while the total crustal ones are represented by either oscillatory or fault movements, with dislocations of various types. The folding intracrustal movements include block folding, which results from the relative displacements of blocks of the earth's crust, folding of squeezing type (e. g. saline diapirs), folding of general fusion and deep folding. Oscillating tectonic movements are classified into those that are general and the undulatory ones.The former find their expression in the form of synchronous elevations or subsidences of large parts of the earth's crust. The undulatory movements give rise to prominent uplifts and depressions on the continents. The fault intracrustal as well as overall crustal movements are accompanied by the formation of normal faults, reverse faults, shear faults and overthrusts of various order.

In accordance with *V. Khain's classification* tectonic movements are divided into *essentially vertical* and *essentially horizontal* ones. As far as the depth of excitation sources and the spheres of their manifestation are concerned, they are classified into global, upper mantle (deep), crustal and surface varieties. Global movements cover all the spheres of the globe. Upper mantle movements are generated below the sole of the earth's crust and are spread over considerable parts of the earth's crust the areas of which can be compared with geosynclinal regions. Crustal movements find their expression within the confines of the consolidated earth's crust and are particularly intensive above the Conrad discontinuity. They are conditioned by the displacements of magma, dislocations of isostatic equilibrium, instability of the Earth's magnetic field, and the displacements and turning of large parts of continents. Surface (sheet) movements are associated with processes in the sedimentary mantle (e. g. saline diapirism).

It should be pointed out that all types of tectonic movements are closely connected with each other and are most fully manifested in the mobile (geosynclinal and orogenic) zones of the earth's crust. The interconnection is expressed in the complex combination and intertransfer of various types of movements. Thus, vertical movements are found to be correlated with the horizontal ones, movements that are smooth are related to those of the ruptured variety, and so on.

Characteristics of Tectonic Movements

A very important feature of tectonic movements is their continuous and general manifestation within the geological history. The manifestations of tectonic movements have been recorded not only in the course of long geological epochs, but also in the historical period, i. e. in the memory of mankind. According to the time of their manifestation and also in correspondence to the methods of investigation the tectonic movements of the earth's crust are subdivided into recent, present, and ancient movements, the last being referred to the movements of the past geological epochs.

Recent Movements.They include those that manifest themselves over the historical period, i. e. within the memory of mankind, and have been going on

until now. Recent movements are highly complicated. They are characterized by irregular velocities at which the marked points or lines are displaced and not infrequently by loop-like trajectories with vertical and horizontal components. Vertical movements have an oscillatory (more precisely, reciprocate) character, while that of horizontal movements is ordered.

Mainly there are two methods in studying recent vertical movements. They are the historical and geodetic methods. The former is based on the observations of the position of various engineering constructions in relation to the level of the sea, large lakes and rivers, and the study of archaeological and graphic documents providing us with the information on the changes in time of a certain coastal line position, etc. Beginning with the eighties of the nineteenth century water-measuring observations have regularly been conducted at many ports of the world, i.e. the sea level is instrumentally estimated relative to a constant datum marks (tide-gauges), which helps to assess in quantitative terms the elevations and subsidences that take place. The changes in the level established with the aid of water-measuring observations are, on the one hand, conditioned by natural (eustatic) changes in the level of the World Ocean connected with the alterations in the volume of water mass or the relief of the floor, while, on the other, with the uplifts and sinkings of the shores. The recent century has been remarkable for a regular rise in the ocean level, which has been going on at the rate of 1.2 mm per year. Since the recorded changes in the level have higher values and a different sign, they are mainly related to the vertical movements of the coastal land. The following are some of the examples.

A greater part of contemporary Netherlands is found to be below the level of the North Sea. It is protected from the ingression of the sea by high dams (up to 15 m), the building of which in length and in height has been in progress in the course of nearly ten centuries. The velocity at which the subsidence takes place in this region comprises approximately 0.5-0.7 mm per year.

In the Soviet Union the ancient city of Khersones, the ruins of which can still be seen near Sevastopol, presents no smaller interest. The city walls of Khersones, including the lower part of the contemporary gate consisting of two tiers, were erected several centuries B.C.; when in the sixth-twelfth centuries A.D., as a result of the submersion the walls were drowned, an arc was constructed over the foundation of the gate. At present, owing to the elevation which came in place of subsidence, this original two-storeyed gate is found to be above the sea level.

The regions of Finland and Northern Sweden adjoining the Gulf of Bothnia experience at present elevations that take place at the rate of about 1 cm a year. As a result of the uplifts a large number of islands have become peninsulas, and the towns of Uppsala and Eskilstuna, which were designed to be ports and which were the capital of Sweden in different times are now situated at a distance of 60-25 km from the sea shore.

On the New Land the fishermen's huts once built at the edge of water are now found far away from the sea. Today Leningrad is nearly half a metre higher than St. Petersburg of the days of Peter the First. As far back as 1745 the Kanin Peninsula was represented on maps as an island.

An example of ascending movements that is of no minor interest is the district

of the town of Egmorte in the south of France. Even the name of this town (which is the French for 'dead water') reflects its very singular fate. It was once built as a large seaport whence as far back as the thirteenth century campaigns to Egypt and Tunisia were fit out. At present it lies twenty kilometres away from the coast of the Mediterranean Sea.

The geodetic method consists in the repeated levelling, or, otherwise, can be considered as an instrumental method by means of which the recent vertical movements can be evaluated in quantitative terms. For this purpose at some points along certain lines (for instance, railway tracks) periodic changes of elevation datum marks are made followed by the subsequent correlation of these measurements with the data furnished by the water-measuring observations at ports. Thus the repeated levelling has made it possible to establish that within the period from 1920 to 1948 the territory of Donbass and the Ukrainian crystalline shield had undergone elevation at the rate of 10 mm a year as compared with Rostov-on-Don. The rate at which the Azov-Kuban basin is subsided reaches 3-5 mm per year, while the annual subsidence of the Terek basin is 6-7 mm.

In the USSR the repeated levelling of high precision is conducted on special geodetic polygons organized in a number of regions of the country (the settlement Garm in Tadzhikistan, Ashkhabad, Tashkent, the Lake of Baskunchak, the Kola Peninsula, etc.). The number of polygons of this kind in the Soviet Union is more than 20.

The repeated levelling results in compilation of maps illustrating the recent vertical movements in the European part of the USSR (1963) and Eastern Europe (1973). From the data obtained it follows that the recent vertical movements take place at the rate from some fractions to several millimetres, less often more than 10 mm a year. In the vast majority of cases the sign of movements is correlated with the structural plan, thus showing the inherited nature of uplifts and troughs. The movements in mountainous regions (the Caucasus and the Carpathian Mountains) are characterized by greater velocities and the range of contrast. However, there are areas on the platforms too (e. g. the central part of the Ukrainian shield on the Russian platform) where the velocities of elevations are not smaller than, for instance, in the Caucasus (over 10 mm per year). In general, the modern epoch is distinguished by a high rate at which vertical tectonic movements take place (Fig. 30).

In comparing vertical movements in geosynclinal and platform regions it becomes apparent that there is a marked divergence in the velocity gradient, i. e. in the change of the movements rate per distance unit. On platforms the vertical movements of the same intensity and sign cover vast territories. In mobile belts vertical movements are to a greater extent differentiated according to area, i. e. the correlated waves of uplifts and subsidences are much narrower than on the platforms. The velocity gradients on platforms are hundreds, thousands of times smaller than in mobile belts. It is therefore assumed that the maximum amplitude of vertical movements of the earth's crust corresponds to the scope of marks of the contemporary relief and consequently makes approximately 20 km.

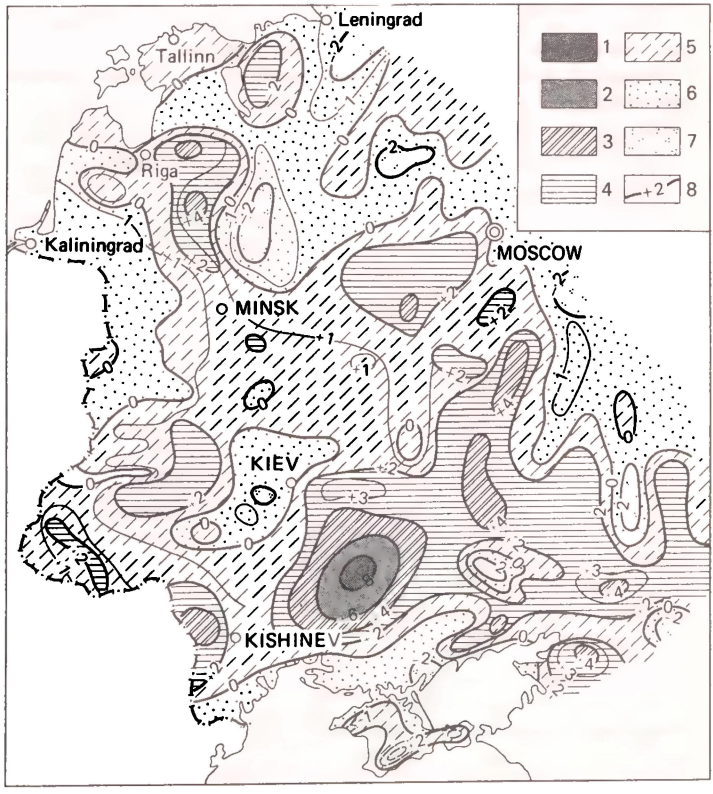
The analysis of recent horizontal movements has only recently been undertaken. Its principal method was that of repeated triangulation, which was succeeded by trilateration, i. e. the method that presupposes the use of laser

rangers to measure the length of not one, but all the sides of a triangle. The more precise methods of repeated measurement of the distance between individual points make use of laser reflectors installed on the Moon or artificial earth satellites, as well as the registration of radio signals from quasars (long-basing radiointerferometric method).

The velocity of recent horizontal movements is considerably higher than that of the vertical ones and comprises 2 cm a year (the maximum being 25 cm a year). Besides, the character of horizontal movement is ordered rather than the reciprocate one. This is exactly what accounts for the fact that the total amplitude of horizontal movements (hundreds and thousands of kilometres) is found to be much higher than the amplitude of vertical movements (20 km).

Thus, the contemporary displacement velocities along the shear faults in

FIGURE 30. A sketch-map of the velocities of contemporary vertical movements of the earth's crust within one part of the East-European Platform (according to Yu. Meshcheryakov). Elevations of various intensity (mm/year):
1–from ± 8 to ± 10; *2*–from ± 6 to ± 8; *3*–from + 4 to + 6; *4*–from + 2 to + 4; *5*–from 0 to + 2.
Subsidences of various intensity (mm/year):
6–from − 2 to 0; *7*–from − 4 to − 2; *8*–isometric lines



California make 2 cm a year, and the total amplitude of displacement has reached 520 km. Arabia and Africa are separated along the Red Sea rift at the rate of 1 cm a year, while the total amplitude has made 120 km (since the Cretaceous period). Over the past forty years in the Gorm polygon the displacement of the Pamir towards the Tien Shan has been taking place at the rate of approximately 2 cm a year. The most significant horizontal displacements have been established along the large faults dissecting the mid-oceanic ridges. Their amplitude is as high as 1 000 km and more.

The analysis of vertical and horizontal displacements of the Earth's surface is supplemented by the change of its slopes with the help of special instruments – tiltmeters, while for studying deformations deformographs are employed. Besides, in the underground mining operations (Tien Shan and Kola Peninsula) the tension in the earth's crust is also measured. This made it possible to establish that the earth's crust is everywhere influenced by marked horizontal compression stresses which are apparently much greater than the value of geostatic pressure conditioned by the overlying rock mass. This phenomenon is particularly significant in the underground exploitation of mineral resources.

The tectonic movements that manifested themselves in the Neogenic and Quaternary periods, i. e. in the nearest geological past, are referred to as *modern movements*. Their velocity is by one order lower than that of *recent movements* and varies from 0.1 to 1 cm a year. Movements of this kind enter into the domain of a relatively young science called *neotectonics*.

Recent tectonic movements are connected with the formation of the main characteristic features of the contemporary relief of the Earth's surface, the development of denudation and accumulation processes, the emergence of structural forms (uplifts and troughs), also including structures, the development of which is being in progress. The discovery of these structures is of great practical importance for exploration of oil and gas deposits, distribution of which is most closely related to recent movements, as well as for the prospecting of placer deposits, a number of ore deposits (antimony, mercury, arsenic, etc.) in the construction of atomic and hydroelectric power stations, port construction, and so on.

The more intense the recent tectonic movements are, the greater reflection they find in the relief. Thus, within the confines of mountainous structures of the folded-block type, the mountain ridges formed in the recent period (Tien Shan, Sayan Mountains, Altai) correspond to the zones of uplifts, while the intermontane areas are correlated with the regions of depression. The basic elements of the relief of plain areas are also connected with them. Thus, on the Russian platform the main river systems are confined to the regions of recent troughs, while the watershed areas are attributed to the areas of uplifts. Since these movements find their reflection in the forms of contemporary relief, as well as in the character of the occurrence of recent (Neogenic and Quaternary) deposits, their analysis is mainly conducted with the help of geomorphological and geological methods.

Geomorphological methods are based on a detailed investigation of contemporary relief forms. This includes the study of marine and river terraces, ancient coastal lines of various water basins, the characteristic features of river

valleys, estuarine parts of rivers, coral structures, etc. The geological methods comprise the analysis of the distribution of facies and the degrees of thickness of most modern sedimentary rocks, as well as the research of folded and faulting deformations touching upon the Neogenic and Quaternary deposits.

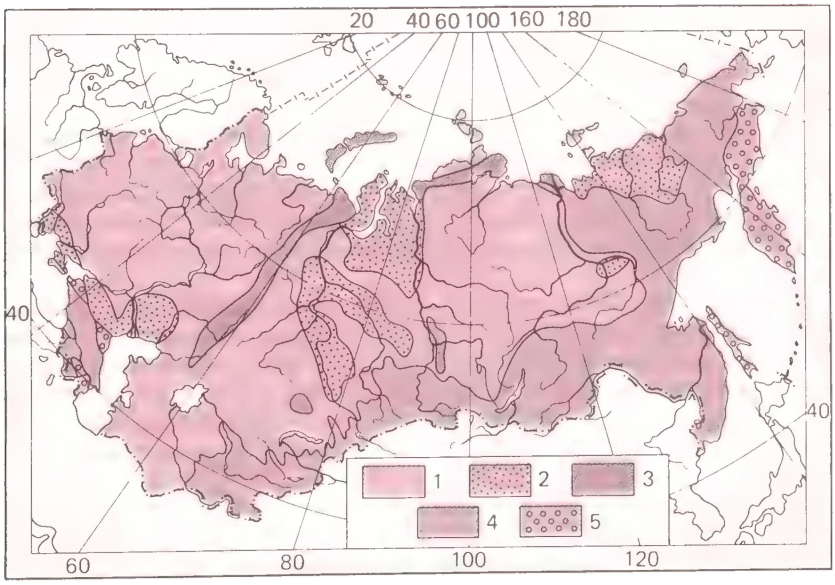
The synthesis of all the data referring to the manifestation of recent tectonic movements finds its expression in the maps of recent tectonics (Fig. 31). On these maps the colour designations show the distribution of present uplifts and subsidences. The amplitude of elevations is estimated according to the marks of the levelling plane and the contemporary relief. The amplitude of subsidences is evaluated by the position of the sole of Neogenic deposits in the depressions.

The movements of the past geological epochs cover all the more ancient tectonic movements which manifested themselves in the Pre-Neogenic period. The velocity of ancient tectonic movements lies within the limits of 0.01-0.1 cm a year. These movements are usually not reflected in the contemporary relief and are inaccessible for direct observation. Hence, in studying them the main role is allotted to geological methods based on the analysis of the facies composition of sedimentary rocks, the principal mass of which is concentrated in marine conditions, the distribution of their volume and thickness, stratigraphic sequences (breaks and unconformities), as well as the facies analysis method.

Facies analysis method is based on the study of those conditions under which

FIGURE 31. A map of recent tectonic movements (according to N. Nikolayev and S. Shultz):

1 – region of extremely low manifestations of recent movements; *2* – regions of weak subsidences; *3* – regions of weak elevations; *4* – region of intensive movements with the preponderance of elevations; *5* – region of intensive movements with the preponderance of subsidences



sedimentation takes place and which are expressed in the lithological composition of sedimentary rocks. Facies can be defined as certain types of sedimentary rocks that emerged in the given physiogeographical conditions (e. g. coastal pebble-beds, estuarine sands, lacustrine limestones and others).

The distribution of facies reflects the topography of the floor of ancient basin and its shores, at the same time revealing the areas of land of the given period. In its turn the relief is the reflection of the structure and tectonic movements of this time. The areas characterized by a stable accumulation of marine sediments of large intracontinental basins are always the zones of tectonic subsidences, while the regions of land are typical of tectonic uplifts. The most prominent depths of the sea correspond to the zones of intense subsidence, while the uplifted regions of land may well be correlated with the zones of no less intense uplift. The size of fragments in the coastal deposits as well as the width and thickness of deposits reflect the intensity of the ascending movements of land. Hence, the facies analysis presents a comprehensive picture of the distribution of the regions of subsidence and uplift and the intensity of these movements. This kind of analysis can also be applied to the quantitative assessment of horizontal dislocations.

Vertical tectonic movements are most closely connected with the redistribution of land and sea which have frequently come into view in the history of the development of the earth's crust. Movements of the negative sign lead to the sea invasion upon the given part of land, or *transgression*, whereas the movements of the positive sign cause the retreat of the sea, or its *regression*.

These processes find their reflection in the character of sedimentation. As is known, marine deposits are characterized by a great variety, and their distribution is submitted to definite regularities, depending mainly on the depth of the basin. It is usual that in the coastal zone there is an accumulation of more coarse-fragmental sediments (pebble-beds, gravel, and sands), which are subsequently replaced by argillaceous, and further by organogenic and chemical sediments as the distance from the coastal line becomes more remote (with the increase in depth).

The processes related to the transgression and regression of sea result in that during the whole period of geological development facies of various types have been developed within one and the same part of the earth's crust. The deposits of one kind of facies are accumulated upon another, the former corresponding to the new physiogeographical conditions that exist under the new position of the coastal line.

The displacement of the boundaries of facies zones is called *the migration of facies*. According to the migration character of facies transgressive series of deposits formed during the sinking of territory are distinguished. The analysis of the changes of the facies composition of deposits, i. e. the migration of facies, helps to bring to light the character of tectonic movements that the region under investigation has experienced in the process involving the accumulation of a sedimentary mass.

In the transgressive series of sediments in the vertical section from bottom to top and in the area directed from the shore to the deeper regions of the basin, the coastal and shallow-water facies (pebble-beds and sands) will be replaced by

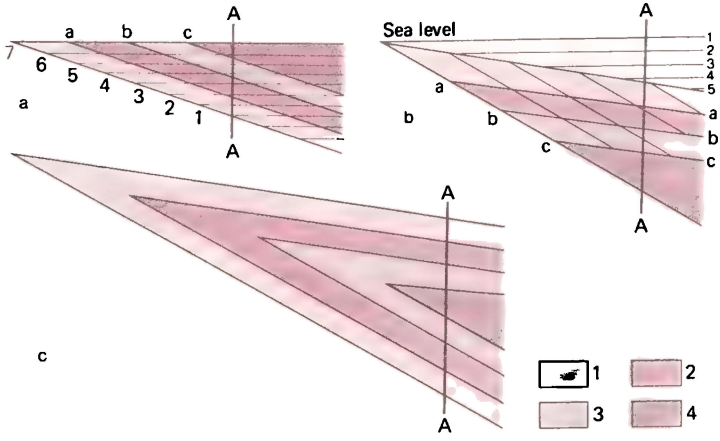
abyssal facies – clays, limestones, and others (Fig. 32*a*). In the case of the regressive series of sediments it will be just the opposite (Fig. 32*b*). In the ascending order in the section and in the direction away from the coastal line the abyssal facies will be replaced by those of the shallow-water variety. Within the complete cycle of sedimentation, i. e. in the case of transgression and regression, the geological section will be remarkable for the presence of both these series of sediments (Fig. 32*c*).

In studying the actual geological sections of certain regions and by discovering in them transgressive and regressive series of sediments, the geologists resurrect the history of the development of tectonic movements of the earth's crust on a given territory. However, it should be mentioned that the migration of facies can be interpreted as a direct reflection of the change of sign and/or the velocity of vertical movements mainly from the closed, midland basins, or in the case of their relatively local manifestation (regressions upon uplifts and transgressions in troughs). In most cases transgressions and regressions are the result of the eustatic movements in the level of the World Ocean.

The analysis of the thickness changes of coetaneous rocks makes it possible to evaluate the scope of vertical movements. The fact is that the total thickness of rocks of a definite stratigraphic subsection is correlated with the value of warping of a given part of the earth's crust. In studying the regularities in the distribution of the degrees of thickness of coeval rocks according to their area, the *isopachous charts* (isopachous lines are defined as lines of equal thickness) enable the geologists to determine the amplitudes and direction of the vertical movements in different parts of the earth's crust. On the other hand, the contrastive analysis of these charts representing various stratigraphic subsections helps to analyse the development of these movements in terms of time.

FIGURE 32. The displacement of facial zones following the movement of the coastal line during transgression (*a*), regression (*b*), and the complete cycle of sedimentation (*c*):

a, b, c – boundaries of facies; *1-7* – temporary boundaries of the sea; *A-A* – a line of vertical section; *1* – pebbles; *2* – sands; *3* – clays; *4* – limestones



Stratigraphic break method is based on the analysis of geological sections according to their stratigraphic sequences. This kind of analysis makes it possible to discover the disturbances of normal stratigraphic sequence of layers in geological sections of particular parts of the earth's crust and fall out of deposits from sections that correspond to a given interval of geological time. Such a disturbance of stratigraphic sequence is referred to as *stratigraphic unconformity*.

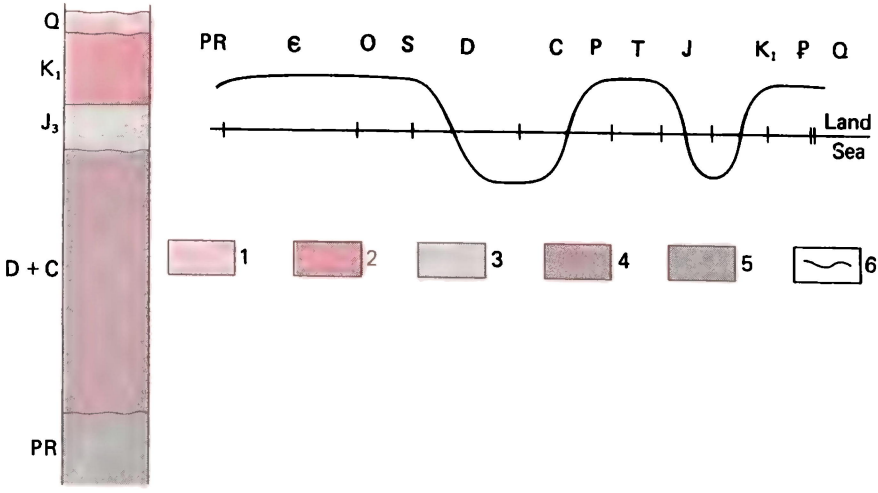
As more intensive sedimentation takes place in marine conditions the presence of stratigraphic breaks shows the continental marine regime change (that is, the sign change of oscillatory movements) when the disintegration processes prevail over the processes of sedimentation.

The schematic geological section of near Moscow bedrocks and also the scheme of oscillatory movements, reduced on its analysis and represented in the form of paleogeographical curve, are shown in Fig. 33.

The volumetric method of investigating vertical movements is based on the estimation of the summary volumes of the deposits according to isopachous charts. These data serve as the starting point for the further evaluation of the average dimensions and velocities of the uplifts and subsidences of the earth's crust within the confines of large territories.

The analysis of formations has a particularly important place among the methods of paleotectonic research. Formations are defined as a regular and stable combination of certain types of rocks that are genetically connected with each other and that emerge in some definite stages pertinent to the development of the main structural elements of the earth's crust. Since it is precisely the tectonic regime that serves as the decisive factor conditioning the isolation of all types of facies, the facies themselves may well be regarded as the reflection of

FIGURE 33. Paleographic curve for the Moscow region (symbols according to the book)



definite tectonic conditions. Hence, the correct determination of the type of facies helps to establish the geostructural zone of its accumulation and the development stage of the given zone. Some of the formations that are called indicators are extremely characteristic of certain tectonic regimes. They include, for instance, the molassic formation, which is typical of the orogenic stage in the development of the earth's crust.

The formations characteristic of large geostructural zones give rise to particular formation series in the section. In addition to this, each structural element of the earth's crust is found to be in correlation with its own formation series. Formations are also responsible for the emergence of lateral series, which characterize the transition from one structural element to another within the area. Vertical and lateral series are represented on the formation profiles. The maps of formations of particular geochronological intervals are used in conjunction with isopachous charts for the compilation of the paleotectonic map, or a compound document reflecting the results obtained from the study of ancient tectonic movements.

The vertical and horizontal tectonic movements are closely connected with each other as far as their intertransitions are concerned. They can be of either the same or different origin. It seems to be erroneous to regard one of these types of movements to be primary and the other secondary. Vertical movements function as a prerequisite for the distribution of denudation and accumulation areas on the Earth's surface. The said movements are known to accompany magmatism, gravitational phenomena, and the formation of various forms of folds and faults.

Horizontal movements are conditioned by the disruptions in the rotational regime of the Earth and other reasons. In the opinion of a number of researchers, the horizontal movements of continents take place owing to the convectional heat flows directed from the mid-oceanic ridges towards the coastal line. Horizontal movements condition the contemporary position of continents, and are connected with the formation of folded and faulting forms in geosynclinal regions, and, presumably, with the formation of magmas too.

The origin of vertical and horizontal movements is apparently conditioned by the processes occurring in mantle and lying outside the lithosphere. These processes find their reflection in the earth's crust to which all its spheres are constantly accustomed.

Tectonic Dislocations of Rocks

The tectonic movements of all types cause deformations of rocks as well as the dislocation of the original conditions of their occurrence. They create new forms of occurrence which are called *tectonic* or *dislocated.* Tectonic dislocations usually find their reflection in the relief of the Earth's surface, and directly influence the strength and stability of engineering structures.

The Main Types of Tectonic Dislocations.The forms of occurrence that the rocks have acquired in the process of their formation are called either *original* or *dislocated.* These forms are different for rocks of different origin. Thus, for magmatic rocks the original forms are batholites, stocks, dikes, necks, and others. The sedimentary rocks, the main accumulation region of which is the

levelled out floor of seas and oceans, are usually deposited in the form of parallel, practically horizontal layers, or beds (Fig. 34a).

In the process of geological development, mainly as a result of tectonic movements, the initial forms of occurrence of rocks can change, in which case new, secondary forms, or tectonic dislocations are formed. The latter are referred to as *dislocations.*

According to the variety of forms and scales of their manifestation tectonic dislocations can be divided into two principal groups, viz. folded and disjunctive dislocations.

Folded, or *plicative dislocations* are expressed in the wave-like bending of the layers of rocks without their discontinuity and hence they are also called dislocations without a break in continuity. The crumpling of rocks into folds is conditioned by the property of solid bodies to undergo plastic deformations. The said property is considerably enhanced with the rise in temperature, all-round pressure and the time during which the load exercises its impact. Therefore, when in certain parts of the earth's crust conditions of this kind are brought into effect even fairly brittle rocks become susceptible to plastic deformations. What should particularly be stressed is the role of geological time, since all the processes are characterized by the duration which is measured in hundreds of thousands and millions of years.

FIGURE 34. Forms of rock occurrence:
a – unbroken gentle dip; *b* – monoclinal attitude; *c* – flexure; *d* – folded attitude

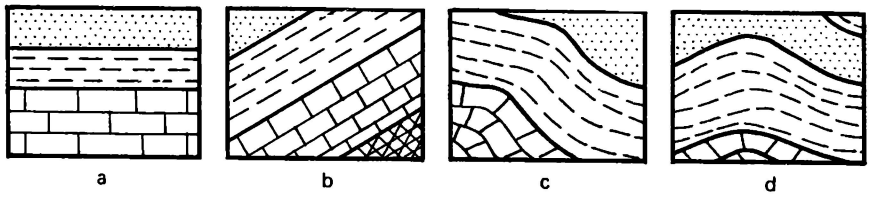
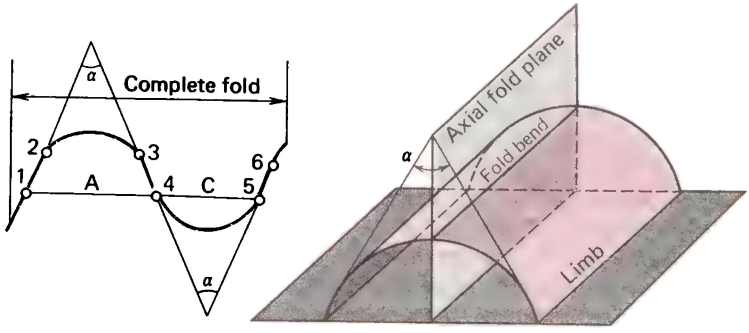


FIGURE 35. Geometrical elements of folds:
2-3 – hinge of anticline (*A*); *4-5* – hinge of syncline (*C*); *1-2, 3-4, 5-6* – limbs of folds; α – angle of fold



Among dislocations without a break in continuity, there are several structural forms. They are: monoclines, flexures, and folds. *Monoclines* are the simplest form of tectonic dislocations. They represent masses of rocks inclined in one direction at one and the same angle (see Fig. 34*b*). The extended, gently sloping monoclines are characteristic of platform regions, while larger ones are typical of the transition zones from platform to mountain-folded areas.

Flexures are defined as structural forms which have the shape of bending or curvature of horizontally deposited or inclined layered masses of rock (Fig. 34*c*). Flexures are usually formed as a result of block displacements of the underlying strata, with the thickness of rocks in the zone of displacement being reduced.

Folds are the basic form of plicative dislocations and represent wave-like bends of layers (Fig. 34*d*). Depending on the direction of the bend, folds are said to be either of *the synclinal* or *anticlinal* variety.

In synclinal folds (synclines) the bend of layers has its convex part directed downwards, and they fall towards each other. The central parts of synclines are characterized by the deposition of younger rocks, as compared with their marginal areas.

In anticlinal folds (anticlines) the bend of layers has its convex part directed upwards, and their fall is oppositely directed. The central parts of anticlines are composed of more ancient rocks than its peripheral regions. The correlated syncline and anticline give rise to a complete fold (Fig. 35).

In any fold there can be distinguished *geometrical elements*, with the help of which its morphology can be described. The main geometrical elements of folds are: limb, core, hinge of fold, numerical scale, angle of fold, axial fold plane, and fold axis.

Limbs are the lateral parts of a fold, where the layers are inclined in one direction. *The hinge of fold* is the place of bending of layers, where one limb is transmitted into another. *The core* of fold is the inner part of the fold adjoining the hinge of fold. *The numerical scale* is the line connecting the points of maximum bendings of any of the layers that form a fold. *The angle of fold* is the angle formed by the imaginary continuation of fold limbs till their intersection. *The axial fold plane* is the plane that passes through all the numerical scales. In a particular case it can be a surface. *The fold axis* is the line of intersection of the axial plane with the horizontal surface.

The forms of folds are highly varied. Their classification is based on a number of different features.

1. *According to axial plane* (Fig. 36, II) folds are classified as upright (*a*), inclined (*b*), overturned (*c*), recumbent (*d*), and reversed (*e*) ones.

In *upright* folds the axial plane is vertical, and the inclination of limbs is not the same. Folds are called *inclined* (oblique), if the axial plane is inclined and the limbs dip at different angles. If the inclination of the axial plane is considerable, the limbs dip in one direction (one limb seems to be turned under another), there emerge *overturned* folds.

In *recumbent* folds the position of the axial plane is close to the horizontal one. Folds, the axial plane of which is situated below the horizontal plane, are called *reversed* (*plunging*) folds.

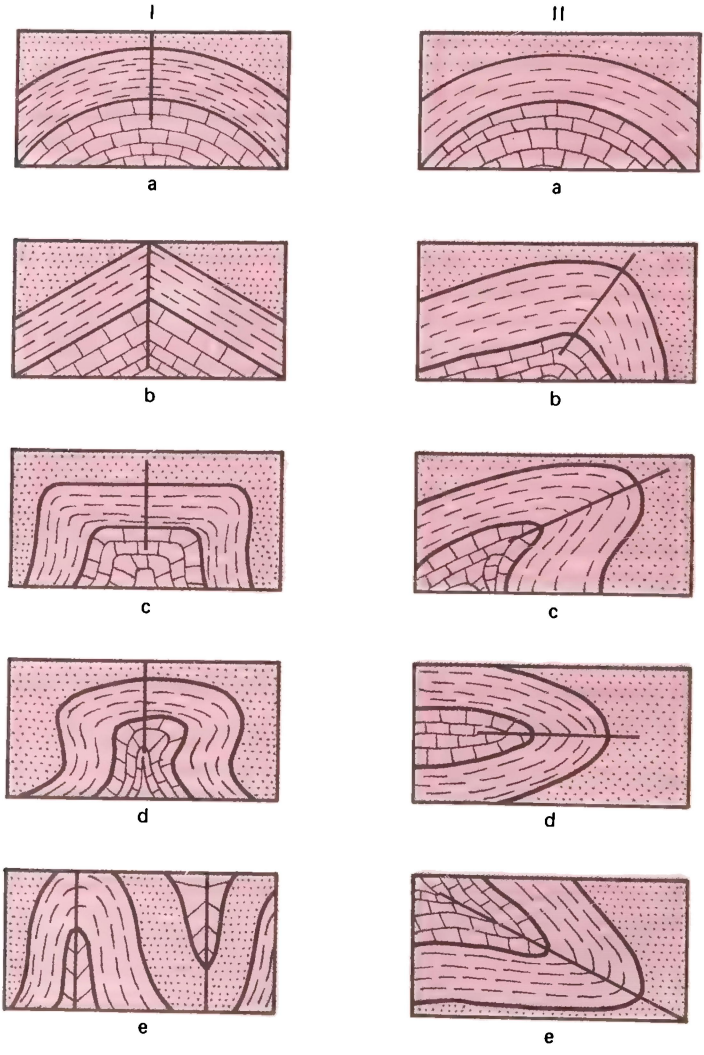
In overturned, recumbent and reversed folds in the limb that is situated above

the axial plane a normal sequence of layers is preserved (young rocks are found to be on top of the ancient ones). In the limb situated above the axial plane the succession of layers is reverse (the ancient rocks overlie those that are of the younger age).

2. *According to the form of hinge of fold and the relation between the limbs* (see Fig. 36, I) folds are said to be of either normal (rounded or sharp), isoclinal, fan-shaped, or coffer varieties.

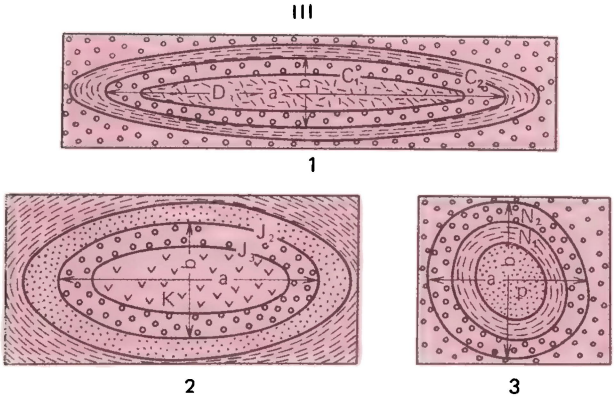
In *normal* folds the curve of fold has either angular (*b*), or rounded (*a*) form. *The*

FIGURE 36. Morphological types of folds



isoclinal folds (*e*) have a narrow curve of fold and practically parallel limbs. *The fan-shaped* folds (*d*) are characterized by a wide curve of fold and a fan-like divergence of limbs. *Coffer* (box) folds (*c*) are distinguished by a flattened curve of fold and sharp limbs.

3. *According to the relationship of the dimensions* of folds (length and width) (see Fig. 36) folds are either linear, brachy-fold, or dome-shaped. *Linear (1)* folds have a narrow and markedly elongated form in the plan, and are formed under an intensive crumpling of rocks. Their length is much greater than their width. In



brachy-folds (the truncated variety) the length is only from twice to 5 times more than the width. Among them brachysynclines (*2, b*) and brachyanticlines (*2, a*) are singled out. *Domes* are anticlinal folds which have isometric contours in plan (*3, a*). Their length can be not more than twice the width. Synclinal analogues of domes are called *troughs* (*3, b*). A specific type of domes find their expression in *diapir folds* (domes with piercement cores) (see Fig. 36 III). They are formed when the highly plastic rocks (salts, clays, gypsum, etc) are extruded upwards, thus giving rise to the core of fold (Fig. 37).

All the folds that are manifested in definite parts of the earth's crust are brought together under the term of *folding*. The folding of linear type is usually expressed within the confines of mountain-folded structures and covers them completely. Individual anticlinal and synclinal folds are grouped into more complex structures, or anticlinoria and synclinoria (Fig. 38).

Brachy-folds, domes, troughs, and flexures are more characteristic of platform regions. Being isolated from each other, they form folding of the intermittent type.

Tectonic faults, or those of the *disjunctive* variety find their expression in the diastrophism of rocks and their rupture along a certain surface. They are most closely connected with those of the folded type. When the stresses that emerge in the earth's crust exceed the ultimate strength of rocks, plastic deformations are transformed into brittle ones and thus the dislocations with a break in continuity are formed.

The faults are divided into two groups: *ruptures with either no displacement or with inconsiderable displacement of rocks and ruptures with their displacement.*

The first group comprises various types of fissures. *Fissures* are defined as ruptures in rocks either with displacement or with a very inconsiderable displacement of disjoint blocks. They are found practically in all rocks, except those of the loose and wetted variety in which fissures cannot be preserved. All the fissures that are grouped within a certain area of the earth's crust give rise to what is known as *jointing*, which is characterized by dense distribution of fissures, the number of their systems and their interrelationship. The jointing of rocks is a phenomenon, which is widely spread in nature, and there is not a single part of the earth's crust which would not be broken up with fissures to a certain extent.

Individual fissures are distinguished by the degree of their exposure; dimensions (i. e. according to their length and depth); the form; the position in space and their relationship to other elements of the tectonic structure (to folds, oriented structure of the intrusive rock, etc.); the activity forces character, which led to the emergence of fissures (tear and shear fissures).

According to their origin fissures are subdivided into *non-tectonic* and *tectonic* ones. The former primarily comprise petrogenetic, or original fissures.

Petrogenetic fissures are created during the formation of magmatic and sedimentary rocks in connection with the relaxation of the fields of mechanical stresses, conditioned by the solidification of intrusive bodies and lavas or the process pertaining to the diagenesis of the sediment. Magmatic fissures (contraction joints) determine the jointing of rocks and can be characterized by

FIGURE 37. Diapir folds (*a* - piercement cores)

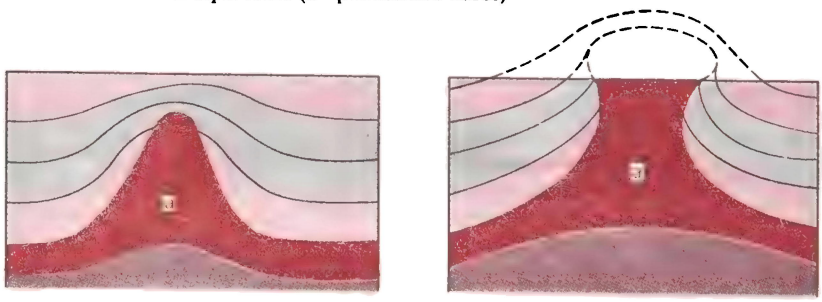
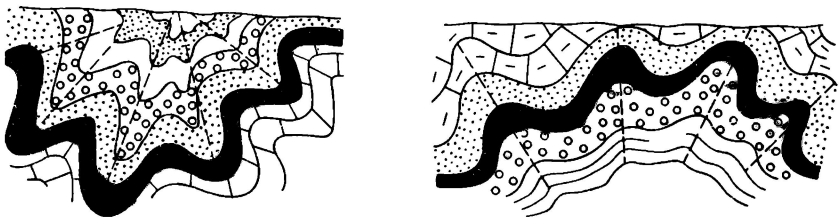


FIGURE 38. Complex folded structures: synclinoria (*a*) and anticlinoria (*b*)



a great extension. In sedimentary deposits during the process involving the transformation of the sediment into a rock (in the course of desiccation, consolidation, and change in volume and temperature) there takes place a layout of diagenetic fissures, e. g. desiccation fissures are usually small in size and do not go beyond the limits of individual layers.

The other group of non-tectonic fissures comprises *exfoliation joint*, formed in surface conditions as a result of the activity of exogenic processes and the gravitational forces of rocks. They include those of the weathering and landslide varieties, as well as fissures in the slopes of river valleys and gorges, connected with the subsidence of slopes, artificial fissures formed in the course of man's activity and its influence on the earth's crust, and, primarily, with the development of the deposits of mineral resources.

Tectonic fissures are formed as a result of the activity of stresses conditioned by tectonic movements. These fissures are usually characterized by considerable length and cross the bedding of sedimentary rocks and magmatic bodies, and are often found to be confined to useful mineralization. Tectonic fissures are, as a rule, grouped into systems, the arrangement of which reflects the character and direction of tectonic stresses (Fig. 39). For instance, in the case of tension stresses there appear the so-called tear faults which often form two perpendicular systems. *Tear faults* are usually exposed. They have an uneven surface, and are deprived of any traces of displacements. The compression gives rise to *shear fissures*, the intersecting systems of which are oriented at an angle of approximately 45° to the axis of compression. These fissures are markedly long, rectilinear, and have a smooth surface. They may well be defined as tight-closed fracture along which inconsiderable displacements of individual blocks can take place.

FIGURE 39. Systems of tectonic fissures in Paleogenic sandy marls (Dagestan)

In faults (paraclasses) there takes place not only the discontinuity of rocks, but also the subsequent displacement of the thus formed blocks along the tectonic fissure, or the *fault fissure*. This group covers such dislocations as normal faults, reverse faults, shear faults, overthrusts, and complex faults.

In any fault with a displacement the following geometrical elements are distinguished: *fault fissure*, or the surface of fracture along which displacement takes place; *walls*, i. e. the displaced blocks of rocks adjacent to the aforesaid surface. When the position of the fault fissure is inclined, the wall situated on top of it is called *the hanging wall*, while the one below the fault fissure is referred to as *the footwall*.

No minor importance is attributed to the determination of *the amplitude of displacement*. The latter are classified into: *the inclined (true) amplitude*, viz. the distance along the fault fissure between the roof and the floor of one and the same bed in the hanging wall and footwall, *the vertical* and *horizontal amplitudes*, or the projections of the true amplitude upon the vertical and horizontal planes respectively; and *the stratigraphic amplitude*, i. e. the distance along the normal between the roof and the foot of one and the same bed in the hanging wall and footwall (Fig. 40).

Normal faults represent faults, in which the hanging wall is lowered, while the recumbent one is slightly lifted, and the fault fissure is inclined in the direction of the lowered wall (Fig. 41*a*). Faults are formed in conditions pertinent to the extension of the earth's crust.

Reverse faults are faults, in which the hanging wall is elevated along the steep (over 60°) fault fissure, while the footwall is lowered, and the fault fissure is inclined towards the uplifted side (see Fig. 41*b*).

Overthrusts are faults with a displacement, which are characterized by a gently sloping (> 60°) fault fissure (see Fig. 41*c*). Extremely gently sloping overthrusts with wave-like surface of the fault fissure and a marked horizontal displacement (covering tens and hundreds of kilometres) are called *charriages* or *overthrust sheets*.

Shear faults represent faults, in which the displacement of blocks with regard to each other occurs mainly in the horizontal direction (see Fig. 41*d*). They are often found to be in combination with normal and reverse faults, and other varieties, thus giving rise to transient dislocations of the strike-slip fault, thrust

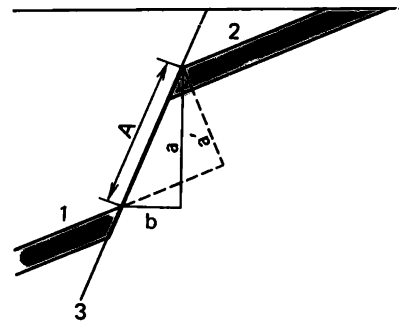
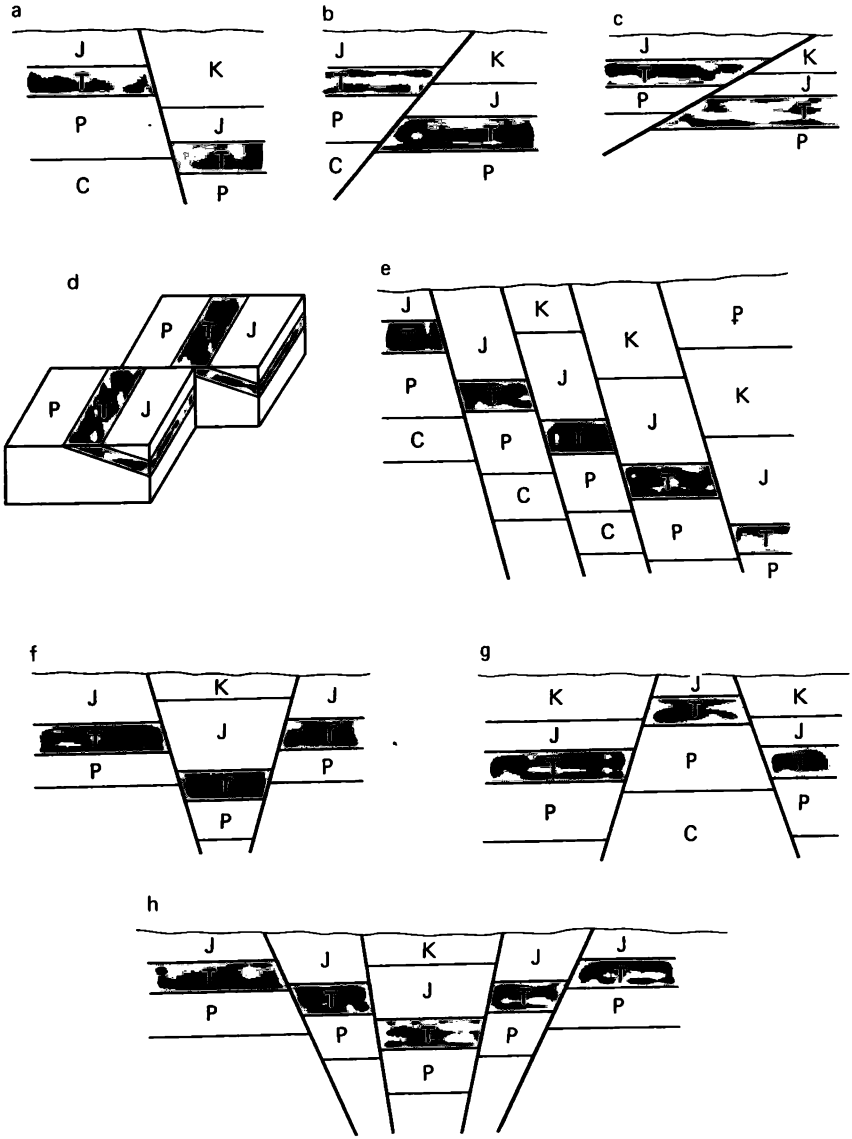


FIGURE 40. Geometrical elements of a fault:

A – inclined amplitude; *a* – vertical amplitude; *a'* – stratigraphic amplitude; *b* – horizontal amplitude; *1* – hanging limb; *2* – recumbent limb; *3* – fault fissure

FIGURE 41. The main types of tectonic dislocations with a break in continuity accompanied by displacement



fault, and other types. Upthrusts, overthrusts, and shifts are usually formed in the process involving the contraction of the earth's crust.

Ruptured dislocations, grouped with each other, form *complex rupture faults*, or step faults, grabens, and horsts. *Step faults* are systems of fault in which each successive wall is lowered as compared with the preceding one (see Fig. 41*e*).

Grabens are faults bounded by the system of normal or reverse faults, where the central parts are lowered with regard to the peripheral parts (see Fig. 41*f*). *Horsts* are also limited by the system of normal or reverse faults, but their central parts are elevated in comparison with the peripheral ones (see Fig. 41*g*). Complex varieties of grabens (see Fig. 40*h*) and horsts are singled out too.

Some types of tectonic deformations in natural exposures are shown in Fig. 42.

In a number of cases the rupture-forming movements accompanied by displacement are instantaneous, in which case they are connected with the manifestation of powerful underground shocks that result in earthquakes.

A special kind of tectonic deformations finds its expression in the so-called *deep faults*. They are long-lived faults of deep-seated deposition (of about 700 km), intersecting the earth's crust and going down into the mantle. These faults are characterized by the length which measures hundreds and thousands of kilometres. Very large blocks of the earth's crust are usually displaced along them. This can be exemplified by the Talasso-Fergana fault which extends itself through the whole of the Tien Shan, the Kuril-Kamchatka fault, those of the Rudnyi Altai, and others.

It should also be mentioned that in nature there exist a large number of dislocations of the intermediate *folded and ruptured type*.

The study of dislocational tectonic movements has an enormous significance, particularly for the exploration, survey, and exploitation of mineral deposits. Suffice it to say that it is precisely the dislocated parts of the earth's crust as the most slackened that are found to be especially favourable for the localization of deposits. The nature of dislocations determines the conditions in which orebodies are situated as well as their morphology. A true appreciation of the character of tectonic dislocation of rock massifs serves as a reliable factor for a successful surveying and development of the deposits of mineral raw materials.

Elements of Attitude. In all those cases when the attitude of various geological bodies and beds of rocks, in particular, differ from the horizontal type, the concept of *elements of attitude* is introduced with the aim of determining their orientaton in space. These elements include: strike, dip, and the angle of dip.

The strike of bed (or any other inclined plane) is defined as its extension (position) with regard to the cardinal points on the horizontal plane. The direction of strike can be expressed by the line of strike. *The line of strike* is a line of intersection of the bed with the horizontal plane, i. e. any horizontal line within the plane of the bed itself.

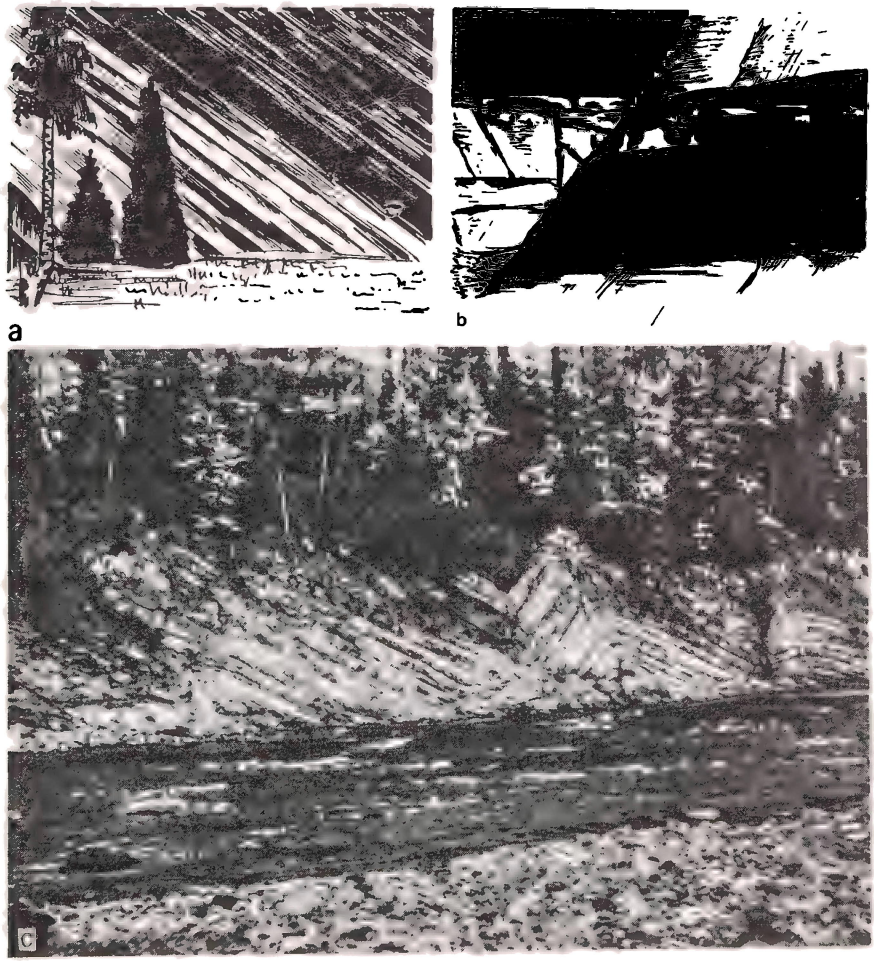
The position of the line of strike as regards the cardinal points is determined by the strike azimuth. *The strike azimuth* is the right-hand horizontal vectorial angle measured from the northern direction of the geographical meridian up to the line of strike. The azimuth can vary from 0 to 360°. Since any line of strike has two

diametrically opposite directions, the strike azimuth can be expressed by two values differing in 180°.

The dip of bed is its position regarding the plane of the horizon. It is established by the line of dip. *The line of dip* is the line of the intersection of the plane of bed with the vertical plane directed towards its greatest slope. Thus, the line of dip and the line of strike are perpendicular to each other. As distinct from the line of strike, the line of dip is the vector. The direction in which the bed dips is also determined by the azimuth.

FIGURE 42. Some types of broken bedding of rocks in conditions of natural exposure:

a – monoclinal folding of red sandstones, Tien Shan (according to G. Gorshkov); *b* – fault of small amplitude in Triassic sandstones and argillites, Crimea (according to G. Gorshkov); *c* – folded bedding of marls in a river valley, Eastern Siberia



The direction of dip is the angle between the projection of the line of strike on the horizontal plane and the northern direction of the geographical meridian. The direction of dip can change from 0 to 360° and is characterized only by a single value.

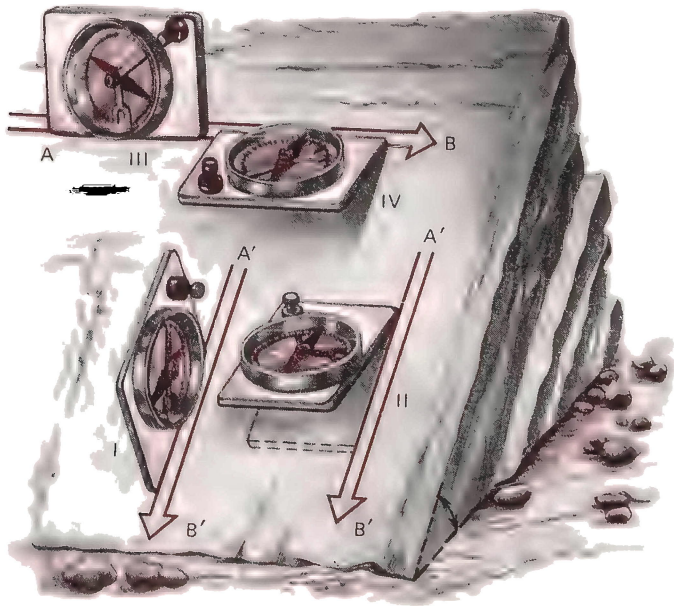
The angle of dip is a dihedral angle formed by the plane of bed and the horizontal plane (or the angle between the line of strike and its projection on the horizontal plane). The angle of dip varies with different inclinations of the bed between 0 and 90°. The elements of occurrence are registered in the following way: Pr. S 255 W; Dip S 135 E 135, ∠ 32.

In field work conditions the elements of occurrence are determined with the help of a surveyor's compass. It is used to measure horizontal (azimuthal) as well as vertical angles. The elements of occurrence of an inclined bed and their measurement with the help of a surveyor's compass are shown in Fig. 43.

The surveyor's compass consists of a round box (body) which is fastened to a rectilinear plate. The body contains a limb with the scale divisions from 0 to 360°. In order that the direct measurement of the azimuths could be achieved, the divisions on the limb are arranged in an anticlockwise order. In the centre of the limb there is an acicular point which holds the magnetic needle, the northern point of which is usually made dark.

In the surveyor's compass vertical angles are estimated with the help of

FIGURE 43. The elements of bedding and their measurement with the help of a surveyor's compass:
AB – line of strike; *A'B'* – line of dip; α – angle of dip; I – determination of the angle of dip; II – determination of the azimuth of dip; III – the finding of the line of strike; IV – determination of the strike azimuth



a clinometer (plumb line), which has a scale (semi-limb) with the divisions from 0 to 90° in both directions from the centre of the semi-circle. The plumb-line oscillates freely only when the position of the compass plate is vertical. When it is required to verify the horizontal position of the compass plate a level is usually situated upon it.

When measuring the elements of occurrence in field-work conditions an even site coinciding with lamination is selected. The estimation can further be conducted in two ways. For steeply dipping beds we first find the position of the line of strike and the value of the angle of dip. For this purpose the compass is set on the chosen plane with its long side in a vertical position and the plumb-line down. In addition to this the magnetic needle must be fastened. Without separating the compass from the plane it is rotated round a point A, and the indications of the clinometer are followed incessantly. The maximum deviation of the plumb-line will correspond to the true angle of the bed's dip, and the direction of the long side of the compass in this position will coincide with the line of dip (Fig. 43, I). The azimuth of dip can be determined if, without separating the compass from the discovered line, the compass is shifted to the horizontal position, with the magnetic needle released and the measurement taken by its northern point.

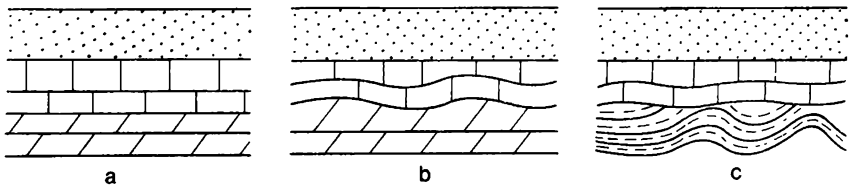
One should bear in mind that in measuring the line of dip the north of the compass's limb must necessarily be directed towards where the bed dips (Fig. 43, II).

Since the strike azimuth differs from the line of dip in 90°, it can be easily estimated if we either add to the line of dip 90° or subtract from it the same value.

When the position is of the gently sloping type we find first the line of strike. In this case the compass in the vertical position is placed with its long side on the selected plane and by turning it round point A, we find its position in which the plumb-line on the semi-limb indicates zero (Fig. 43, III). In this position, the long side of the compass coincides with the line of strike. For measuring the strike azimuth the long side of the compass, which has been set into the horizontal position, is superimposed upon the line that is found, in which case the end-points of the magnetic needle show the values of the two strike azimuths. As a rule, the measurement is taken according to the north end-point (Fig. 43, IV).

When it is required to find the line of dip, the base of the compass is placed on the selected plane so that its short side coincides with the line of strike and its

FIGURE 44. Layers of rocks and conditions of their bedding:
a–conformable bedding; *b*–parallel stratigraphic unconformity; *c*–angular unconformity



long side falls within the line of dip. The method of establishing its azimuth is given above. After that the compass is again brought into the vertical position and its long side is superimposed upon the line of dip, in which case the plumb-line of the compass will show the value of the angle of dip.

The elements of occurrence measured at the given point are plotted on a map or plan and indicated by means of a short arrow oriented towards the line of dip and the longer line which is perpendicular to it and coincides with the strike of bed. The value of the angle of dip is inserted next to the sign. The elements of occurrence can be measured in the natural outcrops of rocks, called geological exposures, as well as in the course of mining operations.

All this makes it possible to collect information on the conditions of occurrence of the whole complexes of rocks. The study of geological sections makes it clear that the relationship between the said complexes can be quite different. In the case of a conformable bedding the boundaries of the rock beds are practically parallel to each other, and their succession in terms of age remains unimpaired: in the ascending order the younger rocks are consecutively replaced by the older ones. Relationships of this kind prove that the process of sedimentation is continuous (Fig. 44*a*).

It is not infrequent that when the boundaries of layers remain parallel, certain stratigraphic subsections fall out of the section. In this case we speak of *stratigraphic* or *parallel unconformity*, which serves as proof that sedimentation is characterized by breaks that are brought about by the tectonic movements of the earth's crust. This gives rise to the so-called washout surfaces that begin to appear in geological sections (see Fig. 44*b*).

However, in a large number of cases there occurs not only a stratigraphic break, but also various conditions of occurrence of base and top rocks. This kind of unconformity is called angular. Thus, in Fig. 44*c*, we find that the lower complex of rocks is crumpled into folds, while the upper one is bedded horizontally.

FIGURE 45. The position of rocks of Cenozoic (*a*), Mesozoic (*b*), and Paleozoic (*c*) age characterized by angular unconformity (according to M. Ivanova)

The warping of the earth's crust, which led to the accumulation of rocks of the lower complex has presumably been superseded by the uplifting and crumpling of rocks into folds. The elevation above the sea level was accompanied by an intensive denudation and the levelling out of the relief. The new warping of the earth's crust became responsible for the transgression of the sea and the accumulation of horizontally deposited layers of the upper complex. Geological sections can also be remarkable for the presence of several angular unconformities (Fig. 45).

Complexes of rocks characterized by various conditions of occurrence and isolated from each other by angular unconformity are called *structural stages* (*layers of geology*).

Meaning of Tectonic Movements

Tectonic movements hinder the levelling out of the Earth's surface, thus constantly giving rise to differences in the hypsometric levels of the individual parts of the earth's crust. This is the main prerequisite for the development of the exogenic geological processes, and evidences the inseparable dialectical unity of endogenic and exogenic processes. The direct result of tectonic movements finds its expression in the changes of contours that are undergone by continents and oceans, as well as the phenomena pertaining to the transgression and regression of seas.

The tectonic movements, functioning during the whole period of geological development, are the basic factors in the formation of the current structure of the earth's crust.

Disturbances in the bedding of rocks formed in the course of tectonic movements enhance the penetrability of the earth's crust and become responsible for the emergence of regions of low pressure, thus promoting the appearance of magmatic chambers, the displacement (migration) of magmatic melts and not infrequently the ore-bearing solutions that are separated from them. Lastly, tectonic movements of various character are to a great extent conditioned by the processes involving the metamorphism of rocks.

The study of modern and recent oscillatory movements is not only of scientific, but also of great practical importance. They are particularly to be taken into account in the building of long-term engineering structures, e.g. ports, canals, hydropower stations, mining enterprises and others. An inadequate geological substantiation of engineering structures in the regions where modern and recent movements manifest themselves most overtly can lead to highly undesirable consequences. Thus, the dockyard built in California in the years of the Second World War was threatened by inundation in several years' time and a protective dam had to be constructed for its preservation.

The irregular intensive uplifts and subsidences of the earth's crust are liable to deteriorate the functioning of the water-supply systems and the underground gas and oil pipelines.

The investigation of directivity and intensity of modern and neo-tectonic movements has an important significance for the rational organization of the search for various mineral resources. For instance, in the exploration of the

placer deposits of precious metals and diamonds it is necessary to discover the zones of local uplifts, where natural 'dams' are created, and where the richest varieties of placers are formed.

In the oil and gas bearing regions the zones of intensive manifestations of modern and recent movements are found to be most promising for the concentration of oil and gas, since the fissures that are formed in the course of tectonic movements function as their conductors.

Chapter 9 Earthquakes

Such threatening phenomena of nature as strong earthquakes had for long been the concern of people and had been frequently mentioned in various documents and historical chronicles. However, they have only recently become the object of scientific research and are at present studied by a special science known as *seismology*. Hence, all the phenomena related to the emergence and manifestation of earthquakes are called *seismic*.

The term 'earthquake' covers any vibration of the Earth's surface brought about by natural causes. In accordance with the factors conditioning them, earthquakes can be divided into three main groups:

Volcanic earthquakes are connected with the processes of volcanism and are thus developed only in the regions of contemporary volcanic activity, either accompanying or preceding the eruptions of volcanoes. They emerge as a result of deep explosions of gases, emitted from the magma and hydraulic shocks of magma, which moves along the channels of complex form, etc.

Denudation earthquakes, or earthquakes *due to collapse*, are spread less widely than the volcanic ones. They result from the collapses of considerable masses of rocks, mainly in the mountain regions, the sinking of underground cavities, e. g. karst caves and large landslides.

The third group of earthquakes is called *tectonic*. Earthquakes belonging to this group are characterized by maximum force and account for 95% of all the earthquakes that are registered. According to current judgements tectonic earthquakes are connected with the short relaxations of mechanical stresses that have continuously been accumulated in the depths of the Earth and that have emerged during the reciprocal displacements of individual blocks of lithosphere. Since relaxations of this kind are manifested in the formation of faults and 'instantaneous' displacement along them of individual blocks of the earth's crust or the mantle, tectonic earthquakes actually represent nothing else but a particular type of contemporary dislocation movements. It is exactly the tectonic earthquakes that are in the main discussed below.

Mechanism of the Emergence of Earthquakes and Their Recording

The continuously accumulated elastic stresses in the Earth's mass on reaching the ultimate strength of rocks deteriorate the latter with the result that there appears a more or less extended rupture. The walls of this rupture are

immediately displaced with regard to each other along the fault fissure, while the energy that is released is spread in all directions from the rupture in the form of elastic vibrations, or seismic waves, the three basic types of which are given below.

Longitudinal waves (*P*) are defined as the reaction of the medium to changes in volume and are propagated in solid, liquid, and gaseous bodies. They represent the vibrational movement of the particles of which the substance consists in the direction pertinent to the propagation of waves. In rocks of the earth's crust they are propagated at the rate of up to 5-6 km/s.

Transverse waves (*S*) are the result of the reaction of the medium to the change in form. Hence, they cannot be propagated in liquid and gaseous media, since substances of the former and the latter kind do not react to the change in form that they have. In cases like these the particles entering into the composition of a particular substance vibrate in the direction perpendicular to that towards which the waves move. The velocity at which transverse vibrations propagate is of the order of 3-4 km/s.

Surface waves (*L*) emerge only at the boundary surface of two media distinguished by their aggregate state, as, for instance, on the Earth's surface, which separates the lithosphere from the atmosphere, or on the water surface, which serves as a boundary between the hydrosphere and the atmosphere. They are characterized by the velocity that is smaller as compared with that of transverse and longitudinal waves and are rapidly extinguished with the increase in depth as well as in the distance from the epicentre, though within the latter they can become responsible for considerable damage.

The propagation velocity of seismic waves depends to a great extent on the composition, structure, and physical condition of rocks. The said dependence, when generalized, can be formulated thus: in consolidated rocks the seismic waves are propagated at a greater rate than in the loose ones. At the same time, the destructive force of earthquakes is considerably stronger in the loose and poorly-consolidated rocks than in those of the more compact varieties.

The length of seismic ruptures is different: viz. from several kilometres (8 km during the earthquake in Tashkent in 1966) to hundreds of kilometres in the case of the 1960 earthquake in Chile. As a result of the earthquake in the Gobi district of Altai (1957) a whole system of ruptures was formed, the total extension of which was approximately 700 km. In a large number of cases seismogenic ruptures are found to be correlated with the long-lived ruptures of ancient deposition.

The place in the earth's crust or the upper mantle where the instantaneous displacement of rocks took place and the underground shock occurred is called *the focus of an earthquake*. In its centre the *hypocentre* is situated. The region that extends itself upon the Earth's surface on top of the hypocentre (its projection of the day surface) is called *the epicentre*. The area within the confines of which the earthquake reaches the maximum degree of intensity is known as the pleistoseistic area, but since the epicentre is situated in its centre it can also be referred to as *the epicentral area* (Fig. 46).

Depending on the depth at which they emerge, earthquakes are classified as either *surface earthquakes*, with the hypocentre at the depth of up to 10 km;

normal earthquakes, the depth of which varies from 10 to 60 km; those of *the intermediate variety* (between 60 and 300 km); or *the deep-focus ones*, that are remarkable for their depth exceeding 300 km. The preponderant earthquakes on the territory of the USSR are of the normal (46%) and surface (36%) varieties. The intermediate type accounts for about 18%, while the deep-focus ones are very inconsiderable and are mainly recorded within the confines of the Far East. The epicentre of deep-focus earthquakes is placed at 760 km depth.

The hypocentres of earthquakes can be situated not only below the surface of continents, but also under the seas and oceans. During the *seaquakes* it is not infrequent that there appear great elliptical waves, or *tsunami*. When they are closer to the shore their height can reach 30-40 m. On hitting the shore the damage they cause to coastal structures and ships is very great indeed.

The duration of earthquakes can vary from several seconds to some months (and even years). Owing to the gradual intermittent release of mechanical stresses there takes place a recurrence of underground shocks. The initial prominent shock is usually followed by a succession of weaker ones, or *aftershocks*, and the span of time covering this process is called *the period of earthquake.* The aftershocks can last for 3 or 4 years after the manifestation of the main shock, though their frequency gradually decreases. Thus, during the earthquake in Alma-Ata in 1887 over 600 shocks were registered.

FIGURE 46. A diagram of a seismic region:

1 – epicentre; *2* – region of pleistoseismal line; *3* – isoseismic zones; *4* – isoseismals; *5* – seismic rays

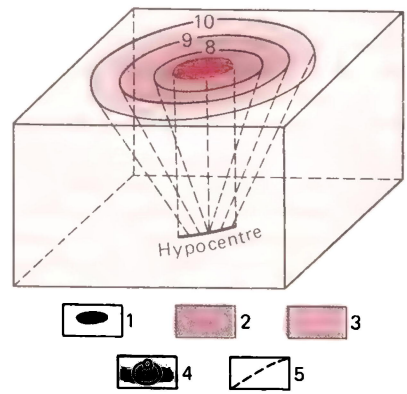
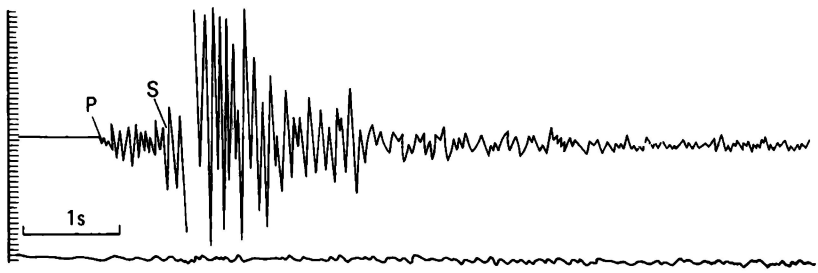


FIGURE 47. Seismogram:

P – delivery moment of longitudinal waves; *S* – the same of transverse ones



Hence, the earthquakes are not once occurred, but they are the result of the long developing process involving the movement of matter within the inner parts of the Earth.

Earthquakes are registered and studied at the so-called *seismic stations*, the number of which in the USSR is at present nearly 100. These stations are provided with special instruments (*seismographs*), which register the incoming elastic oscillations caused by earthquakes. Seismographs can magnify the amplitude of oscillations hundreds and thousands of times and are thus capable of recording even the slightest oscillations coming from the remotest centres of earthquakes.

The recording received by means of the seismograph is called *seismogram*. All of them share exactly the same features (Fig. 47). At the beginning of a seismogram we have oscillations of a rather small amplitude, in its middle part the range of oscillations reaches its maximum, and at the end it becomes small again. This can be explained by the fact that seismic waves do not come all at one time. The beginning of oscillations speaks of the arrival of longitudinal waves. After a certain period, which is determined by the remoteness of the given station from the epicentre of the earthquake, there appear marked vibrations, which evidence the presence of transverse waves. Following several sharp zigzags the seismogram once more records inconsiderable fluctuations of the curve which are shortly succeeded by the regular vibrations of great amplitude and period characterizing the arrival of surface waves.

The analysis of seismograms makes it possible to speak of the duration of an earthquake, the quantity and amplitude of individual vibrations, the depth of the epicentre, its location, etc. The exact position of the epicentre is usually established with the help of the resection method from different stations. The epicentres discovered by seismic stations are then plotted on a map, which enables the geologists to have a sufficient amount of information concerning the geographical distribution of earthquakes and to determine the seismoactive zones.

Force, Energy, and Magnitude of Earthquakes

Such concepts as force, energy, and magnitude are employed when it becomes essential to characterize various types of earthquakes. *The force*, or *intensity*, is taken to be the external effect of an earthquake, i.e. its manifestation on the Earth's surface. The force of earthquakes is estimated by the value of acceleration of the particles, constituting the Earth's surface under the impact of the shock produced by earthquakes. Different seismologists have suggested various kinds of *scales of earthquake intensities* to measure the degree of force. They are based on the results achieved by means of direct observations of the factors causing the destructions, as well as on the 'psychological perceptions of the people themselves'. Since 1952 a 12-point seismic scale has been adopted in the Soviet Union. A 10-point seismic scale is in Europe and a 7-point seismic scale in Japan.

Earthquakes reach maximum force in their epicentre. When diverging from the epicentre the force of underground shocks decreases. The points at which an earthquake has made itself evident with exactly same force is contoured with

lines that are called *isoseisms* (see Fig. 46). In the USSR the earthquake region is outlined by isoseism of four points. Due to the heterogeneity of the composition of the earth's crust the actual isoseisms maps can have a highly complicated configuration.

Strong earthquakes represent catastrophic phenomena the drastic consequences of which inflicted upon mankind cannot possibly be compared with any other phenomena of nature. Thus, for instance, in Japan during the earthquake of the 1st of September 1923, which lasted for not more than some seconds, 128 000 houses were completely destroyed, and 126 000 dwellings partly damaged. Nearly 143 000 people were killed and lost, and 100 000 were wounded.

The devastating earthquakes can be felt over vast distances. For instance, in 1940 the earthquake in the Carpathian Mountains caused earth tremors in Moscow, Voronezh, and Kharkov. In Moscow the tremors continued for several minutes; near the Carpathians they were more prominent and lasted for a greater period of time.

The disastrous earthquakes can be said to include those that were in Lisbon (1755), California (1906), Messina (1908), Tokyo (1923), Iran (1935), Chile (1939 and 1960), Nicaragua (1972), Guatemala (1976), Tien Shan (Chinese People's Republic, 1976), Mexico (1985).

The points on the scale express the relative force of earthquakes, and, since every single earthquake is accompanied by the release of some amount of elastic energy, the all-important task consists in determining the value of this energy (E) as an objective index of the force of an earthquake. One of the most widespread formulae for calculating *the energy of earthquakes* belongs to B. Golitsyn:

$$E = \pi^2 \rho V (\alpha T)^2$$

where V is the velocity at which the seismic waves are propagated; ρ represents the density of the upper layers of the Earth; α is the amplitude of displacement; and T indicates the period of vibrations.

The energy of earthquakes is usually expressed in ergs (E) or joules (J). It varies within the wide limits from 10^{10} to 10^{25} E. For instance, the energy of Ashkhabad earthquake (1948) is estimated as 10^{23} E, the Gobi-Altai earthquake in Mongolia (1957) reached the figure of 10^{24} E, in Chile (1960) and Tashkent (1966) it was 10^{24}-10^{25} and 10^{20} E, respectively. In order that we could get a better idea of these figures, one would not err to mention that the energy of a single earthquake is several million times greater than an explosion of an atomic bomb.

However, no direct method of establishing the energy of earthquakes is devoid of most tangible difficulties. Hence, it was suggested by the American seismologists Ch. Richter and B. Gutenberg that for the characterization of earthquakes the concept of their *magnitude* (M) should be employed instead of the energy of the focus. Let at some distance from the epicentre the seismogram give us the displacement referring to particles of soil A (in microns). The amplitude A will be greater than that of A_0, or the amplitude of some very inconsiderable earthquake, which is taken for the standard. The ratio of A to A_0 serves as an index according to which earthquakes are compared. For practical purposes it is more convenient to use the logarithm of this ratio, which is exactly

TABLE 7. Intensity (Force), Magnitude, and Energy of Some Earthquakes

Place and year of earthquake	Intensity, points	Magnitude, M	Force E, J
Ashkhabad, 1948	10	7.3	$3 \cdot 10^{16}$
Chile, 1960	11-12	8.6	10^{17}
Alaska, 1964	11-12	8.5	10^{17}
Tashkent, 1966	8	5.3	$3 \cdot 10^{13}$

what determines the magnitude, i.e.

$$M = \log \frac{A}{A_0}$$

In actual cases M varies from 0 (when the earthquakes are slight) to 8.8 (in the case of disasters). Empirically it has been made possible to receive the following relationship between magnitude and energy:

$$\log E = \alpha + \beta M,$$

where α and β are the empirical coefficients.

Table 7 gives the main characteristic features of some of the strongest earthquakes.

Geographic Distribution of Earthquakes and Their Prognosis

The observations of earthquakes that have been made in the course of many centuries, as well as the results furnished by the seismic stations that have been registering earthquakes for the past few decades provide every opportunity for the scientists to single out those parts on the Earth's surface that can be confined to strong earthquakes, or the so-called *seismic regions*, as well as areas, where earthquakes are either rare or not characterized by any marked degree of intensity. They are called the *aseismic regions*.

The analysis of maps showing the seismicity of the Earth shows that the most prominent seismic regions on the Earth are *the Pacific* and *the Mediterranean zones* (Fig. 48).

The former corresponds to approximately 68% of all the earthquakes, in addition to which the vast majority of them are of the deep-focus variety. The Mediterranean seismic zone accounts for over 21% of all earthquakes.

As some distance away from the main parts where earthquakes are manifested there are other seismic regions, e.g. a number of mountain structures in Mongolia and China, the Baikal region, the region of the Great Lakes in Africa, etc.

On the territory of the USSR the seismic regions include: the Carpathian region, the Southern Crimea, the Caucasus, Southern Turkmenia, the eastern highlands of Central Asia, the zones of mountain elevations from Altai to the

Sayans, the Baikal region, Southern Primorye, Sakhalin, the Kuril Islands, and Kamchatka.

The irregularity in the geographic distribution of earthquakes is by no means accidental, but it is conditioned by the geological development of individual parts of the earth's crust. On the whole, all earthquakes are connected both in space and genetically with the mobile sections of the earth's crust, in which the modern intensive and differentiated tectonic movements find their expression. First and foremost these parts of the earth's crust include young mountain-folded structures, mid-oceanic crests and rift zones, as well as regions of continents and oceans remarkable for their jointing.

It should be mentioned that the regions characterized by the manifestation of earthquakes coincide, in the main, with those regions where volcanic activity is developed. In a number of cases the direct bond between these two phenomena are most apparent, for instance, when strong earthquakes bring to life the volcanic activity. Thus, in 1952 in Peru and Chile strong earthquakes activated 25 volcanoes, while the 1960 earthquake in Chile made 14 volcanoes come to life again. All this can serve as evidence of the unity of earthquake and volcanism factors that are associated with the general process involving the movement of matter in the depths of the Earth.

Sometimes earthquakes are the signs of volcanic eruptions. This can be illustrated by the earthquakes in the region of the Ploskii Tolbachik volcano, the eruption of which took place in 1975-1976. The very first earthquakes had begun ten days before the eruption of the volcano; the strongest of the earthquakes occurred before the eruption actually took place, while when the latter was in progress, the earthquakes were evidently less prominent.

Earthquakes cannot possibly be considered as rare natural phenomena. Every year seismic stations register several hundred earthquakes on Earth. Most of them are fortunately of the least prominent variety. According to the estimates made by seismologists the average number of earthquakes per year comprises 1-2 disastrous ones, 9-15 earthquakes of the nine-point variety, and those of the eighth and seventh points number 50-100 and 300-500, respectively.

The enormous destructions caused by earthquakes make the prognosis of these threatening phenomena of nature of the first importance. In order that an earthquake could be known in advance it is necessary that its place, force, and time should be determined.

The first part of this problem, i.e. the prognosis of the place and force of the future earthquakes is already being solved. The solution of this problem is based on the compilation of *the maps of seismic zoning*. The basic task set before the latter consists in getting information of the maximum force that the future earthquakes can have within a certain region in future. This kind of task is solved by means of a thorough analysis of seismic regime of a particular territory over an extensive period in the closest association with the characteristic features of its geological structure and development.

In the USSR the first map of seismic zoning was compiled by G. Gorshkov in 1937. In the years that followed the map underwent numerous improvements and its variant is shown in Fig. 49. The analysis of the map reveals that a considerable part of the territory of the Soviet Union refers to seismically

FIGURE 48. The seismicity of the Earth (according to N. Shebalin):
1 – zones of great catastrophies; *2* – earthquake zones of medium force; *3* – zones of micro-earthquakes; *4* zones of deep earthquakes, the depth of which is more than 100 km

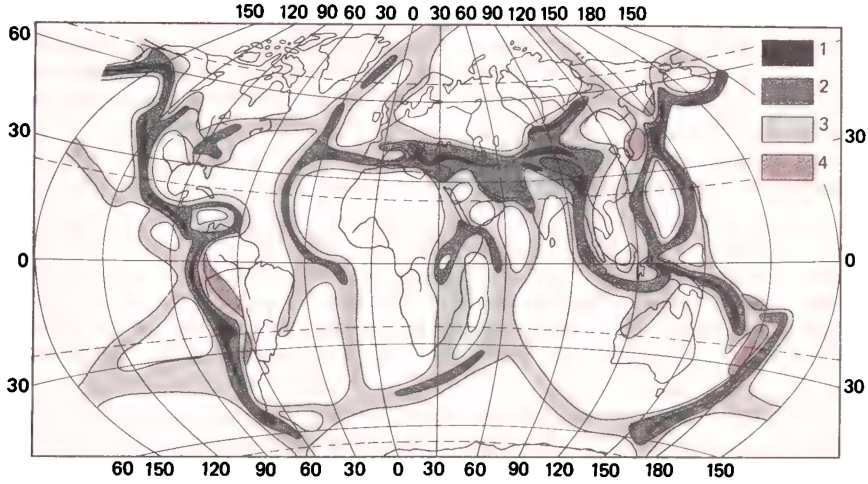
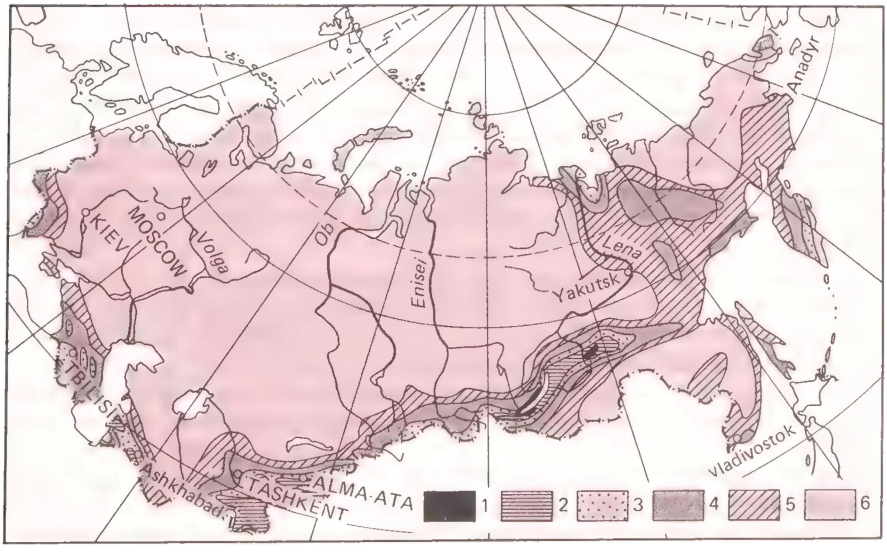


FIGURE 49. Seismic zoning of the USSR territory (according to the data supplied by the Institute of Geophysics of the USSR Academy of Sciences). Zones of earthquakes (in points):
1 – ten; *2* – nine; *3* – eight; *4* – seven; *5* – six; *6* – aseismic zone or the zone of earthquakes with intensity less than six points



dangerous regions. In the south of the Ukraine, the Crimea, the Caucasus, and the Eastern Siberia there exists a possibility of earthquakes the intensity of which can be as high as 7-8 points. In some regions of the Carpathian Mountains, Central Asia, the Baikal region, within the confines of Kopet-Dag, the Tien Shan, and the Pamirs earthquakes can have the intensity of 8-9 points. Much stronger earthquakes are possible in Kamchatka and the Kuril Islands.

Seismic zoning is a task of great significance for the country's national economy, since it provides the necessary information on the seismic peculiarities of various regions and cannot possibly be left unheeded when the planning and building of different kinds of engineering structures are in progress.

In estimating the seismic danger what should be taken into consideration in addition to the tectonic situation itself is the local conditions: viz. the characteristic features of the relief, the properties of rocks, the depth at which the underground waters are deposited, etc. The experience gained from the observations of the destructive consequences of earthquakes has made it possible to discover certain regulations. Some of them are the following. With all other conditions being equal, the widely exposed valleys are found to be less susceptible to tremors than the parts of the territory with a hilly and mountainous relief.

The velocity of seismic waves depends on the composition and properties of rocks. In hard rocks it is considerably greater than in the loose ones, though the amplitude of vibrations and the acceleration of particles are markedly higher in those of the brittle variety. Besides, loose rocks more readily lend themselves to deformation than the hard ones. Since in seismic regions rock massifs undergo less destruction, it becomes necessary, whenever possible, to build all engineering structures precisely on their basis. If loose deposits constitute the slopes, particularly if they contain water-bearing horizons, the earthquakes are noted to be most destructive.

The problem of evaluating the impact of geological conditions is solved by means of seismic zoning. Depending on the potential seismic danger the building of engineering structures presupposes the use of certain methods of seismic construction (the choice of materials, antiseismic constructions, the easing of the roofing, the smaller number of storeys, the storey-by-storey belts made of reinforced concrete and armo-bricks, etc.). In the USSR the official norms of seismic construction are functioning, which, when appropriately employed, provide every opportunity for the buildings and other structures to be preserved during the most violent earthquakes.

The other part of the problem, viz. the prognosis of the exact time of the future earthquake, has not yet been fully solved, though the research work in this direction is now being conducted. At present the solution of this problem promises to render the following main possibilities:

1. instrumental (with the help of tiltmeters) evaluation of the deformations of the Earth's surface (slopes, bends, etc.), which usually precede an earthquake;
2. observations of the changes in the magnetic field within the periods prior to any earthquakes;
3. the study of the changes of elastic properties of rocks, entering into the

composition of the earth's crust, in the region where there is a probability of an oncoming earthquake.

Short-term forecasts of earhquakes in subterranean conditions can be provided if the systematic rise in rock pressure, the increasing rate at which the rock fragments bounce in the process of face operations, sound effects, etc., are taken into consideration. Since any earthquake is a phenomenon that is governed by the laws of nature and is never haphazard as far as its occurrence is concerned (to say nothing of the fact that its manifestation presupposes a lengthy process in the depths of our planet), there is every reason to believe that this highly complicated problem in natural sciences will be solved in the future.

Chapter 10 Magmatism. Magmatic Rocks

Magmatism. It is one of the most important endogenic geological processes, which plays a significant role in the formation of the earth's crust. Approximately 95% of rocks of which the earth's crust is composed, owe their origin to the process of magmatism.

Magmatism is a highly complicated geological process which involves the formation of magma in the earth's crust or the subcrustal region, its migration into the upper horizons of the earth's crust and the development of magmatic rocks.

Magma. The term is applied to natural, predominantly silicate melts saturated with gases that are dissolved in them. The composition of magma is characterized by the predominance of exactly the same chemical elements which, in the main, constitute the earth's crust, viz. oxygen, silicon, aluminium, iron, calcium, magnesium, potassium, and natrium. However, as compared with rocks, magmas are distinguished by a marked quantity of easily volatile compounds, e.g. water vapours, sulphurous compounds, carbon dioxide, hydrogen chloride, fluoric hydrogen, ammonium chloride, nitrogen, and others.

Owing to the high pressure that exists in the depths of the Earth, the volatile compounds are found to be in a dissolved state within magma, thus diminishing its viscosity, increasing the degree of its mobility and the chemical activity with respect to the enclosing rocks. According to experimental data the content of volatile components in magma can be as high as 12%.

Factors Conditioning the Origin and Migration of Magmatic Melts

According to the views held by scientists today magmatic chambers emerge through the periodic local melting of the substance entering into the composition of either the earth's crust or the mantle, caused by the change of thermodynamic conditions, i.e. pressure and temperature.

What are the main reasons, which lead to the change of thermodynamic conditions? As is known, the Earth's temperature becomes regularly increased with the depth. At the depth of about 100 km it comprises 1 300-1 500 °C. If the

pressure were equal to that of the atmosphere, the given temperature would be conducive for any rock to be transformed into the state of melt. However, the predominant pressures existing at these depths and measured in thousands of megapascals considerably enhance the melting point of rocks, thus hindering their transition into the liquid phase. The distortion of this equilibrium within a certain part of the territory becomes mainly responsible for the local transition of a substance into the liquid phase and leads to the formation of *primary magmatic chambers.* In most cases they appear in the lower horizons of the earth's crust or in the upper mantle, and most often in the asthenosphere.

As a result of the displacement of magmatic melts towards higher horizons of the earth's crust there can appear *secondary magmatic chambers.*

The most favourable conditions for the slackening of pressure are apparently created in the course of various tectonic processes, which give rise to complicated and heterogeneous fields of tectonic stresses, and in a number of cases, leading to the disturbance of the earth's crust. Since more intensive tectonic movements are manifested within the confines of geosynclines, it is quite natural that these structural elements of the earth's crust, in particular, are correlated with the comprehensive development of magmatic processes nowadays and in the past of our planet.

The rise in temperature, which can also lead to the local melting of rocks and the formation of magmatic chambers, is associated with different kinds of physicochemical processes, which are accompanied by the evolution of heat. At present, the most important of them are regarded to be the processes connected with the decay of radioactive elements contained in the depths of the Earth. A certain role in the generation of heat can also be allotted to the gravitational processes pertaining to the differentiation of substance and various phase transformations, that take place in accordance with the exothermal scheme, i. e. with the evolution of heat.

According to the views adhered to by some of the scientists, the formation of magmatic sources is a continuous process. They are accumulated in the upper part of the asthenosphere in the form of asthenoliths, whence they are then ascended into the upper horizons of the earth's crust. The movement of magma towards the surface is conditioned, firstly, by hydrostatic pressure, and secondly, by a considerable increase in the volume, which accompanies the transition of solid rocks into the state of melt.

Depending on concrete geological conditions the extent to which magmatic melts can penetrate into the upper horizons of the earth's crust can be different. In the case when magma breaks through the whole mass of the earth's crust the magmatism is said to be *effusive.* If, however, the invasive magma on its way to the Earth's surface solidifies at a certain depth, the process finds its expression in the form of *intrusive magmatism.* Thus, intrusive and effusive magmatism are no more than different forms in which one and the same geological process is manifested.

These types of magmatism are not only different in the forms of their expression, but are also distinct from each other by the character of their end products which are the intrusive and effusive rocks.

Effusive Magmatism

Effusive magmatism, or volcanism, unites all the processes connected with the outflow of magma on the Earth's surface. The volatile components, which, in the deeper regions owing to high pressure, remain within the magma in a dissolved state, are released from it on the way to the Earth's surface. Hence, the magma which has issued on the surface is considerably poorer in volatile substances as compared with its initial content and is called lava.

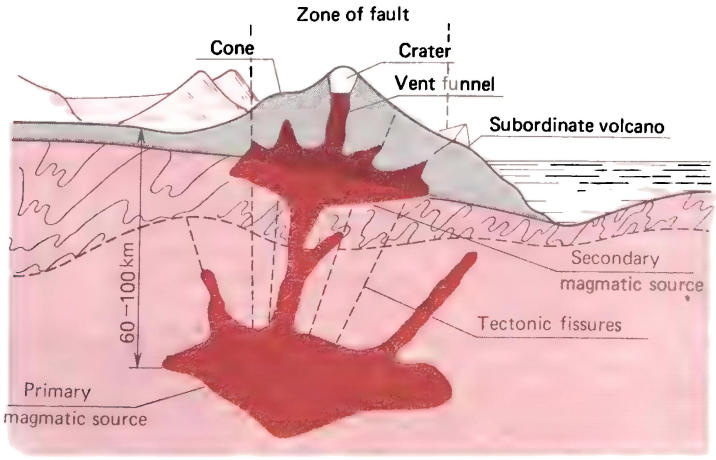
Types of Volcanic Systems. The outflow of lava takes place through the volcanic systems, which, in accordance with their structure, are divided into central- and fissure-type volcanoes.

In volcanoes of *the central type* (Fig. 50), representing geological structures in the form of conical mountains, eruptions occur through the central outlets. Every single volcano has *a vent funnel*, i.e. an effluent channel, along which eruption products ascend from the magmatic chamber. *Crater*, or a bowl-like depression situated at the top of a mountain and forming the end of the vent funnel, is also an inseparable part of any volcano. In a great number of large volcanoes the main vent funnel has ramifications in the form of subordinate vents, called *parasitic* volcanoes.

When the apexes of cones are destroyed as a result of explosions or sinking vast depressions are formed in their place (they can be of up to 15 km in diameter). They are more or less circular in form and are referred to as *calderas*. Inside this crater there can emerge one or several young cones. The forms of geological bodies, formed by the products of the eruptions pertinent to central-type volcanoes are mainly represented by *lava streams* (Fig. 51), and less often by *domes*.

The fissure-type volcanoes lack the central effluent channel and the lava outflows on the surface through deep and extended fissures in the earth's crust. This results in that thick lava *sheets* are formed (Fig. 52).

FIGURE 50. A diagram showing the structure of volcanic systems of the central type



The vast majority of contemporary volcanoes refer to those of the central type. In the period of geological development fissure eruptions were observed in Iceland, where in 1873 the outflow from a 32-km long fissure gave rise to a basaltic sheet with the area of 557 km^2. The most prominent fissure eruptions are connected with the geological past. These are the sheets of basalt in Eastern Siberia, that were formed in the Early Mesozoic period (the so-called traps); the basaltic sheets of the Deccan Highland in India, where the most violent outflows took place at the end of the Cretaceous and during Paleogenic periods; the Neogenic and Anthropogenic basaltic sheets of the Armenian Highland, which cover the area of about 50 000 km^2.

The Products of Volcanic Activity. The products of volcanic eruptions are usually divided into three groups: liquid, solid, and gaseous varieties.

Liquid products of volcanic eruptions are represented by lava. According to their chemical composition lavas can be either acid, medium, basic, or ultrabasic.

FIGURE 51. Lava stream at the foot of the Zhupanova cone-shaped hill in Kamchatka (according to A. Zavaritsky)

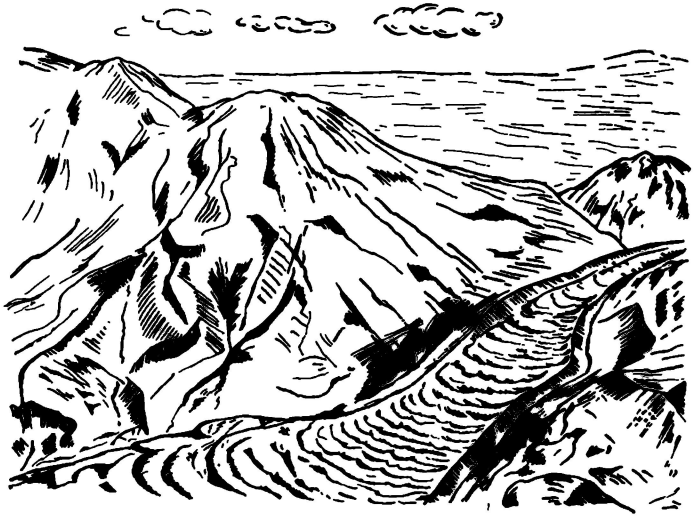
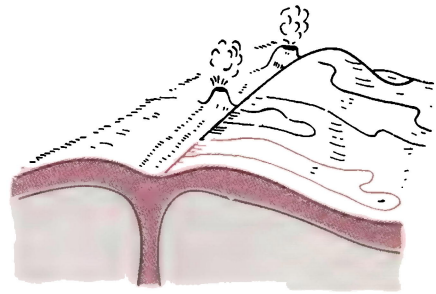


FIGURE 52. A diagram showing the structure of a volcanic system of the fissure type



The chemical composition of lavas determines their most important physical properties – viscosity and mobility – which, in their turn, condition the character of volcanic eruptions.

Thus, lavas of the ultrabasic and basic composition (the basaltic and picritic varieties), which are poor in silica and enriched with ferromagnesium compounds, and the temperature of which at the exit to the surface is nearly 1 200 °C, are characterized by a low viscosity and high mobility. In connection with this they easily spread themselves over considerable distances and form sheets and streams of undulating surface. However, acid and medium lavas (those of the liparitic and andesitic types) – the temperature of which does not, as a rule, exceed 750-1 000 °C – possess a higher degree of viscosity and smaller mobility. At their exit from the crater they quickly solidify, thus forming short streams of block surface, domes, and spines. In the process of lava solidification there emerge effusive or issuing magmatic rocks, which are characterized by hypocrystalline or vitreous structure.

Solid products of volcanic activity are otherwise called *pyroclastic*, since they consist of fragmental material that emerged during volcanic explosions as a result of the ejection into atmosphere and dispersion of huge masses of lava, as well as of the fragments of rocks which are exploded parts of the crater.

Depending on the size of fragments the latter are classified into *volcanic bombs*, the cross section of which is from 5-10 cm to several metres; *lapilli*, with the cross section between 1 and 3 cm; *volcanic sand*, consisting of particles that can be seen with the naked eye (from 0.5 mm to the size of a pea); and *volcanic ash*, representing macroscopically thin dust of various shades of grey colour and consisting mainly of the minutest fragments of volcanic glass.

Volcanic ash is the main part of the solid products of eruptions. In Alaska at the time of the eruption of Katmai volcano in 1912, 20 km^3 of solid products were ejected, 90% of them were accounted for by ash. For 25 hours running there issued an ash torrent that formed in the proximity of the volcano a layer 4 m thick, with the thinnest layer of the same ash covering all continents and oceans.

The distance over which the fragmental material is displaced depends primarily on the dimensions of fragments. Thus, volcanic bombs and lapilli compose mainly craters and volcanic cones; ash particles, however, can be dispersed by the wind to the remotest areas. For instance, the ash of the now extinguished Caucasian volcanoes has been found in the sedimentary formations on the territory of the Voronezh region.

In the later stages as a result of compactness and consolidation of pyroclastic material we have the formation of such rocks as *volcanic breccias* (at the expense of coarse fragmental particles) and *volcanic tuffs* (at the expense of ash).

Gaseous products are released from the vent funnel, subordinate vents and numerous fissures in different stages of volcanic activity. Approximately 60-90% of them consist of water vapour, during the condensation of which the atmosphere becomes very often characterized by heavy rains accompanying the eruptions of volcanoes. In addition to water vapours their composition includes H_2S, SO_2, CO, CO_2, HCl, HF, NH_4Cl, NH_3, H_2, H_2BO_3, and other gases.

The composition of gaseous emissions changes in accordance with temperature. At temperatures higher than 180 °C we have the emission of the so-called *fumarole* gases which contain chlorine, sulphur and carbon dioxides with the predominance of chlorine compounds. Later they are replaced by *solfataric* gases, with the temperature of the order of 180-100 °C, in the composition of which the preponderance is with the sulphurous compounds. At temperatures below 100 °C there is a substantial emission of carbon dioxides called *mofettic*. During sublimation of volcanic gases there often emerge mineral formations which are to be recovered for mining purposes. For instance, near the town of Lordorelo the annual recovery of boric acid, borax, ammonium salt and other products of sublimation makes one thousand tonnes, while the overheated vapour is widely used for the production of electric energy.

The Activity of Volcanoes. The life of volcanoes is remarkable for the periodicity of volcanic eruptions, or for their active eruptive activity as well as for more prolonged periods of rest, when various post-volcanic processes are manifested. It should be mentioned that no particular regularity in the alternation of the periods of rest and active functioning of volcanoes has so far been established. The intervals between eruptions can be quite different–from several years to tens, hundreds, and even thousands of years.

Volcanoes that have not been active within the historical period are considered to be *extinguished.* The volcanoes Kazbek and Elbrus in the Caucasus can serve as examples.

However, the division of volcanoes into active and the extinguished ones is purely tentative since it is never possible to say with any degree of certainty that the volcanoes which are considered to be extinguished will not resume their activity. This is what the famous French researcher of volcanoes G. Tazieff wrote: 'They (volcanoes) are by no means dead, as they seem to those who cannot or do not want to know their "temperament". A volcano can be in the state of "slumber" for one or two centuries and even one thousand years and eventually people will stop thinking about it altogether and will even erase it from their minds. Meanwhile, the geological life of volcanoes does not cease; it is measured in thousands and tens of thousands of years rather than within a shorter span of time. Centuries, and even hundreds of centuries, may pass before the vicinity of the "extinguished" volcanoe will again be threatened by the fatal danger.'

History knows no few examples of this kind. Visuvius, for instance, had not manifested itself in any way till the year A.D. 79. People who lived on its slopes led a quiet life. The eruption of the year A.D. 79 is regarded as one of the most violent and widely-known in the history of mankind. It destroyed the cities of Pompeii and Herculaneum and the little town of Stabiae, and carried away the lives of about 24 000 people. In later years there were violent eruptions of Vesuvius in 1631, 1794, 1872, 1906, and 1944. What proved to be another enormous disaster was the eruption of the Krakatoa volcano in the Sunda Strait, which occurred in 1883 after an interval covering two hundred years. The eruption lasted for several months. As the result of the volcanic explosions two-thirds of the island on which the volcano was situated (with the area of approximately 75 km^2) were exploded, in place of which there emerged a gulf 300 m deep. The ash ejected from the volcano settled upon the area of 800 000 km^2

and in the Sunda Strait hindered the movement of sea vessels. The explosions were succeeded by gigantic waves, the height of which was 35-36 m. Their surge throughout the whole of the Indian Ocean, the Pacific Ocean, and a part of the Atlantic Ocean resulted in the toll of 37 000 human lives.

The active functioning of volcanoes is manifested in different ways, mainly depending on the chemical composition of the outflowing lavas and the content of volatile components in them.

The magma of the basic composition contains a smaller amount of gases; it is more liquid, and its eruption is, as a rule, relatively calm. The eruption of acid magma, which is viscous and slow in its movement, blocking the effluent channels, and which is more saturated with gases, is usually accompanied by volcanic explosions, ejectamenta into the atmosphere of a large number of solid products. According to the character of explosions volcanoes are divided into the following basic types: Hawaiian, Strombolian, Etna-Vesuvius, Pelean, Krakatoa, volcanic pipes, and fissure-type volcanoes.

The Hawaiian and Strombolian Types. They are characterized by the eruptions of lava of the basic (basaltic) composition with the temperatures about 1 200 °C, which, overflowing from the crater run down the slopes at the velocity of 8-10 m/s, thus forming lava streams the length of which is as great as 40-50, and even 80 km. The lava is relatively poor in gases, and the explosions are hardly ever noticed.

The Etna-Vesuvius Type.The lavas connected with this type of volcanoes are usually of the medium (andesite), and more seldom of basic composition. They are viscous, slow in their movement, and their temperature is about 1 000 °C. Not infrequently they block the vent, which leads to powerful explosions, ejecting a great quantity of solid products, such as ash, lapilli, and bombs. The lava solidifies in the form of comparatively short streams (tongues), the thickness of which is 4-5 km.

The Pelean Type. The lavas of these volcanoes are andesitic and are characterized by an exceptionally high degree of viscosity and temperatures of the order of 800 °C. The process of solidification begins within the crater itself, and the lava is slowly extruded from it under the pressure of accumulated gases. The eruptions result in colossal gaseous explosions, which eject a vast amount of solid products and very hot gases. The lava that is solidified forms very peculiar domes and spines.

The Krakatoa Type.The acid and highly viscous lava does not practically flow out on its own, but is ejected as a result of gigantic explosions in the form of a great number of various solid products. Explosions usually destroy volcanic cones and give rise to gigantic calderas.

All the types of volcanoes that have been discussed above are considered to be *polygenic* since they have manifested their activity many times.

Volcanic Pipes.They are referred to a special type of the so-called *monogenic* volcanoes, since their origin finds its expression in a single explosion without any emergence of lavas. The diameter of the pipes usually comprises 80-100 m, and they are filled, as a rule, with solid eruption products. They are also often called *kimberlite pipes* since they have long been known in the vicinity of Kimberley in South Africa – the diamond-mining centre.

The Fissure Type. In the case of this type the lava that outflows is basic basaltic, liquid, and highly mobile. Outflowing along the fissures in different directions, it fills all the depressions of the relief and creates basaltic sheets over the areas that measure up to several hundred square kilometres. The explosive activity is totally absent. The acting fissure volcanoes are known to exist only in Iceland.

The Post-volcanic Phenomena. On the cessation of volcanic eruption various processes that serve as evidence of a preserved activity in the magmatic chamber are observed for a long period of time, i.e. the emission of gases, geysers, hot springs, and mud volcano eruptions.

The emission of gases, which accompanies the eruption of volcanoes, still continues for a long time after it stops functioning. Fumarole, solfataric, and mofettic gases are emitted from the volcanic craters and a numerous fissures in its slopes. Thus, in the Valley of Ten Thousand Smokes in Alaska, which is situated in the vicinity of the Katmai volcano, the latest eruption of which was in 1912, 23 mln litres of vapours are released from its numerous jets every second, 1 250 000 t of hydrogen chloride and 200 000 t of hydrogen fluorine are annually carried away with them. The Mendeleyev volcano on the island of Kunashir, the latest eruption of which was registered in 1894, is even now known to emit abundant amount of gas with the deposition of crystals of native sulphur. In a number of regions in the form of sublimates that are used in industry, there are depositions of boric acid, ammonium chloride, and ferromanganese compounds.

In the regions of contemporary volcanism mineral formations as well as overheated water vapours of volcanic origin can be used for industrial purposes. For instance, in Reykjavik, the capital of Iceland, the greater part of dwellings and a large number of hot-houses are heated by means of thermal waters. In Italy in the neighbourhood of the town of Larderelo enormous reserves of vapour with the temperature of about 200 °C have been discovered, by drilling operations. Under natural pressure of 0.5 MPa this vapour feeds the turbines of an electric power station. In the region of the Pauzhetsk springs in Kamchatka the experimental and industrial electric power station is functioning on volcanic heat.

Hot (thermal) springs have the temperature, which is higher than the yearly average one characteristic of the given locality. In a number of cases their temperature reaches 100 °C. Hot springs are called *thermomineral,* in those cases when the concentration of mineral substances in them is greater than usual. Thermal springs are practically known in all volcanic regions. In the USSR they are widely spread in the Kuril islands and in Kamchatka.

Geysers represent periodically functioning hot (80-100 °C) water-vapour springs. Their name comes from the similarly called region in Iceland, where they first came into notice.

The work of geysers finds its explanation in the following: in the period of rest overheated water is accumulated near the bottom of the geyser channel. Owing to the pressure of the overlying column this water is not transformed into vapour. When in the higher parts of the column the water boils and there begins intense vaporization leading to a reduction in pressure the critical moment arrives, and the overheated water that has instantaneously been transformed

into vapour is ejected outside in the form of a vapour-water fountain of a certain height. Then the process is repeated. The periodicity of eruptions is rather consistent, the intervals between the ejections with different geysers being from 10 min to 5.5 hrs.

Geysers are widely developed in the Yellow Stone Park in the USA, Iceland, New Zealand, and in Kamchatka in the so-called Geyser Valley. Owing to their high temperature geyser waters are mineralized and contain salts of natrium, potassium, magnesium, calcium, and silicon. In connection with this mineral deposits called *geyserites* are usually formed in the area surrounding geysers.

Mud volcanoes represent 1-2 metre high conic elevations with gentle slopes composed of loose sandy-clay formations. The summits of these hills are characterized by craters through which the ejections of mud actually take place. What causes mud eruptions are volcanic gases and vapours, that come up from the bottom along the faults. In their movement they come into contact with loose rocks saturated with water and push them out onto the surface in the form of mud. These formations have very much in common with the mud volcanoes of the oil and gas bearing regions, or the so-called exogenic pseudovolcanoes, in which the mobile force is gases of not volcanic, but organic origin.

The Geographic Distribution of Volcanoes. In the world today there are about 4 thousand extinguished volcanoes and 540 active ones. They are spread on the surface of the Earth most irregularly. There are vast territories with not a trace of volcanic activity, as, for instance, the whole European part of the Soviet Union and Western Siberia; the regions that are rich in volcanoes can be exemplified by the coast of the Pacific Ocean.

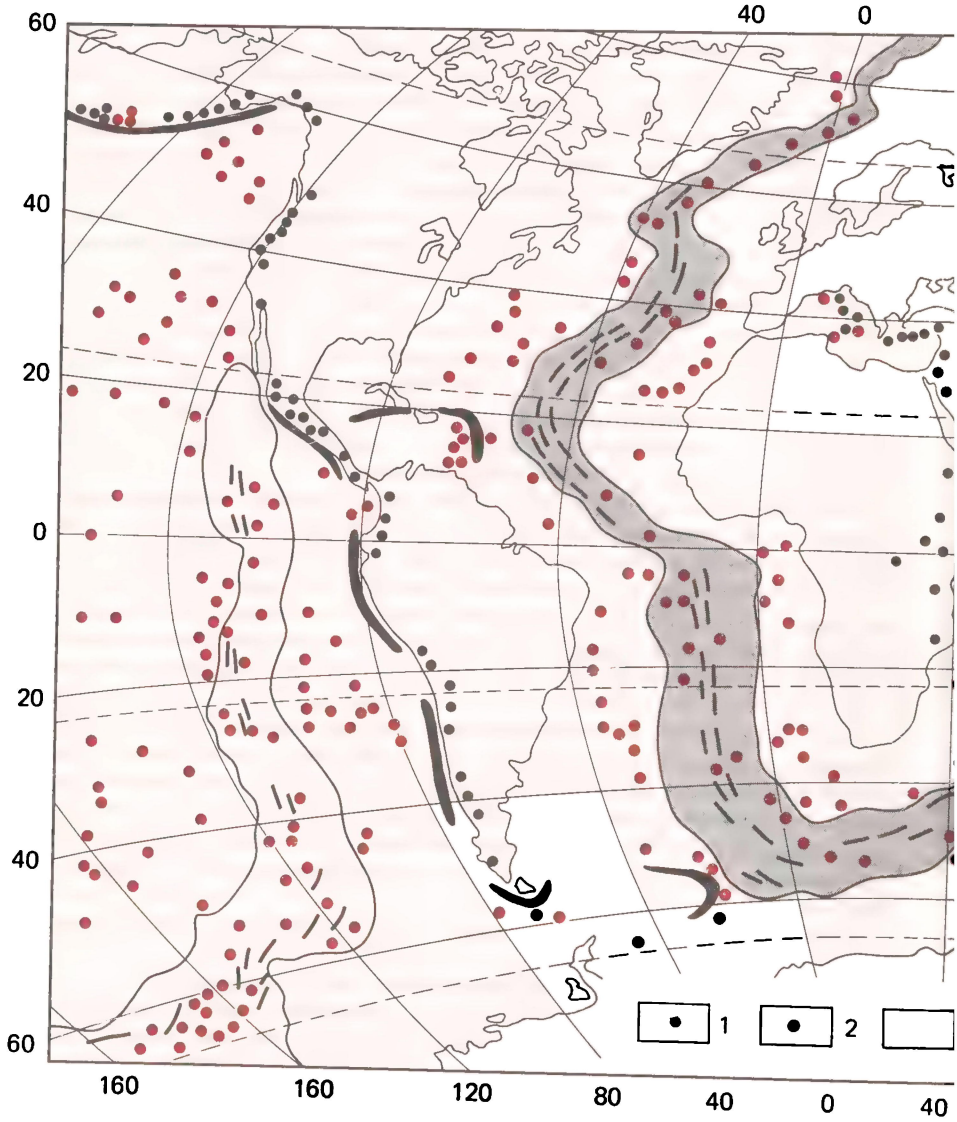
The marked regularities in the geographic distribution of volcanoes can be summarized in the following way. All the zones of recent volcanism are only confined to definite tectonic mobile parts of the earth's crust, within which their location is governed by deep faults. On the continents the regions of this kind are the zones of young mountain-folded structures, transition zones from the continents to the oceanic troughs, and island arcs. In oceans they are represented by mid-oceanic ridges with their rift zones. It is interesting that 77% of the now functioning volcanoes are found to be in correspondence to the transition zone.

The same regularity is tenable for the geological past of our planet. Thus, for instance, the Soviet volcanologists have established that on the Kola Peninsula and in Karelia volcanism actively manifested itself in the Archean and Proterozoic periods, i.e. in the epochs of the geosynclinal development of these regions; in Urals and Kazakhstan this kind of activity can be referred to the Paleozoic period, in Crimea it may be said to be typical of the Mesozoic period, and so on.

The development of volcanism on Earth today can be divided into several zones. The most important of them are the following (Fig. 53).

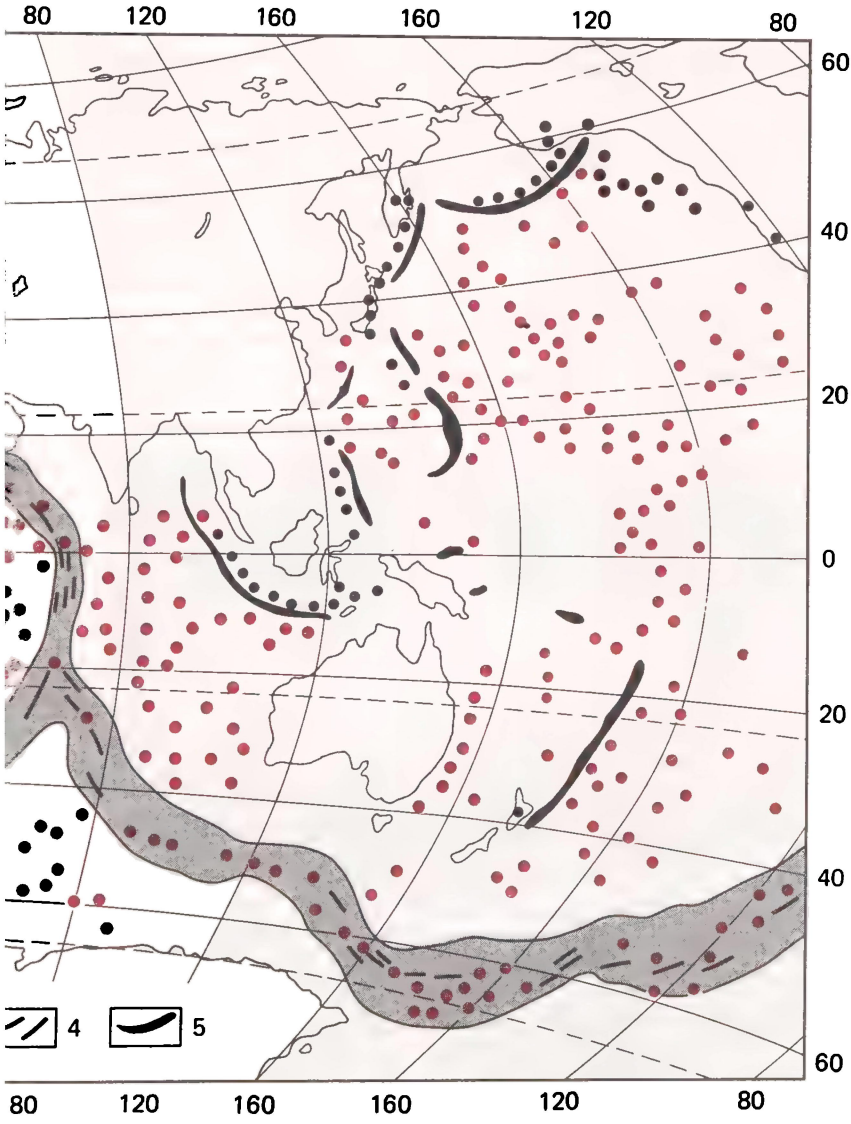
The Pacific zone, or the so-called 'Pacific fiery ring' is the largest. It includes 60% of all the active volcanoes (326) and a large number of those that have recently become extinguished. The Pacific zone extends itself across the Kamchatka Peninsula, the Kuril Islands, the islands of Japan, Philippines, New Guinea, New Zealand, and the Solomon Islands. Then it passes through the north-eastern termination of the Antarctic continent and further along the

FIGURE 53. The geographical range of volcanoes (the Physical and Geographic Atlas of the World, 1964):
1 – volcanoes on land; *2* – submarine volcanoes; *3* – mid-oceanic ridges; *4* – rift volcanic ridges; *5* – deep-water trenches



western coast of America – from Tierra del Fuega through Andes and Cordillera Mountains to Alaska and Aleutian Islands.

The largest acting volcanoes in the USSR occur precisely in this zone. They include Koryakskaya Sopka (Fig. 54), Bezymyanyi, Tolbachik, Avacha, Karym, Sheveluch volcanoes in Kamchatka; Alaid and Sarychev Peak are on the Kuril islands.



The linear and ring arrangement of volcanoes belonging to the Pacific zone is conditioned by the fact that they correspond to the largest in the world zone of fault, which separates the Pacific Ocean basin from the continental massifs of the earth's crust bordering it.

The Mediterranean and Indonesian zone is extended from Alps across Apennines, Caucasus, the mountains of Asia Minor and the islands of Malay Archipelago. This is the zone where the largest volcanoes of Europe are situated, e. g. Vesuvius in Italy, Etna in Sicily, Volcano, Stromboli in the Lipari Islands, and others. Most of the acting volcanoes in this zone are concentrated in its eastern part – in Java, Sumatra, Lesser Sunda and Southern Moluccas Islands.

The Atlantic zone is associated with the central and most elevated part of the submarine Mid-Atlantic ridge and the fault accompanying it. This zone includes the volcanoes in Iceland, the Azores, Canary Islands, Cape Verde Islands, the Antilles, and others. There are 60 active volcanoes in this zone all in all.

The Indian and African zone is mainly represented by those volcanoes that are found on the islands of the Indian Ocean, e. g. Comoro Island, Islands of Mauritius, Réunion, St. Paul Island, and others, that represent the submarine parts of the mid-oceanic ridge. This is also the zone where we find the volcanoes of the interior parts of the continents, which represent a rather rare phenomenon. They are most widely known African volcanoes of Kenya and Kilimanjaro.

FIGURE 54. Koryakskaya Sopka volcano in Kamchatka (photo by G. Tataev)

Intrusive Magmatism

Intrusive magmatism becomes manifested in those cases when the ascending magma is slowly solidified and crystallized at a certain depth and thus forms variously shaped magmatic bodies called *intrusives*. In the later stages, owing to different geological processes many of them are found to be driven out onto the day surface (exposed), and their analysis makes it possible for us to speak of the process of intrusive magmatism.

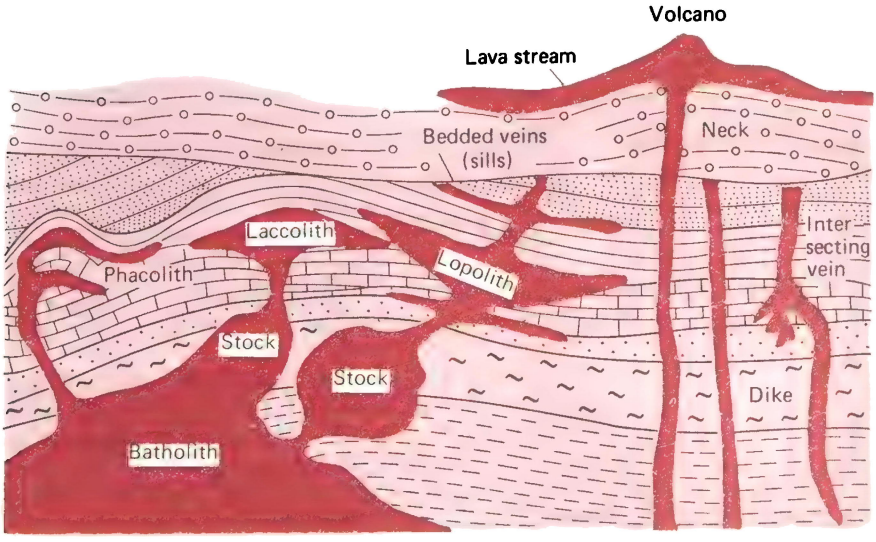
The form of the thus formed intrusive bodies and their contact with enclosing rocks depend on the factors of the intrusion of magmatic melts as well as on the physical properties of the magma itself and the enclosing rocks.

The Forms of Intrusive Bodies. Depending on the relation with enclosing rocks intrusives are divided into *concordant* and the *disconcordant* ones, which dissect the enclosing rocks at different angles. There are instances when an intrusive body is concordant in one part, and disconcordant with the enclosing rocks in some other.

Concordant intrusive bodies include sills (interstratal deposits), laccoliths, lopoliths, and phacoliths (Fig. 55). *Sills* are defined as bed-like intrusive bodies that are formed as a result of the intrusion of magma across the bedding plane of sedimentary rocks. They are most typical of basic magmas, which are characterized by a high degree of mobility. Sills are not infrequently found in groups. The well-known sills are those of the Siberian platform (Siberian traps), which are intermixed in the geological section with rocks of the Carboniferous and Permian systems.

Laccoliths are mushroom bodies which have a convex upper surface and a relatively flat lower one with which incurrent canals are connected. In the plan

FIGURE 55. **Magmatic rocks (forms of bedding)**



they are characterized by a round form and their dimensions range from hundreds of metres to several kilometres in diameter. Laccoliths are usually formed during the intrusion of acid magma, which, due to its high degree of viscosity, possesses a weak degree of permeability and is concentrated only in one place. In addition to this the overlying layers of rocks are uplifted and acquire the form of a dome. Laccoliths are widely developed in the Northern Caucasus and in the region of Mineral Waters (Mashuk, Beshtau, Verblyud, Zmeika, and other mountains), and in the Crimea (Mts. Ayu-Dag, Kastel, etc.).

Lopoliths represent interstratal bowl-like bodies the formation of which is conditioned by the sagging of rocks under the weight of the intruded magma. They consist mainly of basic rocks and are usually of great dimensions. For instance, the Bushweld lopolith in South Africa has the length of over 300 km.

Phacoliths are bodies of relatively small size, which have a lens-shaped form and which are, as a rule, found in the arched parts of anticlinal and synclinal folds.

Among disconcordant intrusives several forms can also be distinguished (see Fig. 55).

Batholiths are known to be the largest kind of intrusive bodies which are spread over the areas covering scores and hundreds of thousands of kilometres, and which are characterized by an elongated and oval form in the plan. In most cases batholiths are confined to the central parts of mountain folded structures and are composed of rocks of granitic composition.

Until recently it has been considered that batholiths represent bodies which have no floor, the roots of which are interconnected with magmatic sources. However, geophysical research conducted in the past few years has provided sufficient evidence that the vertical size (thickness) of a large number of batholiths does not exceed 5-10 km.

The problem pertaining to the origin of batholiths, or more precisely, the one which is concerned with the space they occupy, is highly complicated and lends itself to discussion. There are a number of opinions on this question. According to one of them the ascending magma melts the roof rocks, assimilates them, and thus makes room for itself. In accordance with another hypothesis, batholiths, which are usually formed in the terminal stages of the uplift of mountain folded structures, when intruded into the earth's crust, elevate it, as it were, without disturbing the structure of enclosing rocks on the whole, and, lastly, many researchers associate the formation of batholiths with the process of magmatic replacement (*granitization*) of sedimentary rocks at the place of their original occurrence. This process is brought about by the fact that rocks are influenced by high-temperature fluids of deep origin that penetrate along the fissures and faults of the earth's crust.

Stocks are intrusive bodies of irregular and often cylinder form, the sectional area of which is not more than 100 km^2. As a rule, they are confined to the zones of intersection of various tectonic deformations and can be built of rocks of various composition, from acid to ultrabasic ones. It is not infrequent that stocks are ramifications of batholiths of a larger size (batholithic stocks), but often they also form near-surface bodies, or magmatic diapirs.

Dikes represent flat tabular bodies, which emerge as a result of the process involving the filling of vertical and inclined fissures in the earth's crust with magma. Dikes are composed of rocks of diverse composition and are usually situated in groups. The size of dikes changes within very wide limits. The Great Dike of Zimbabve is known to be the largest. It is 540 km long with the average thickness of 5 km.

Besides tabular dikes of regular form there are fissure intrusives of not exactly regular shape. They are characterised by various bends and ramifications, and are referred to as *magmatic veins.*

Necks are pipelike bodies, representing vents of ancient volcanic systems of central type filled with magma. Their diameter measures from several metres to 1.5 km. Necks are filled with chilled magma that often contains fragmental material.

Intrusive bodies can be formed at various depth. Batholiths and batholithic stocks are usually formed at considerable depth, in connection with which they are called *abyssal* magmatic bodies. The formation of other intrusives is usually associated with moderate and small depths, and they are referred to as the *hypabyssal* or semi-abyssal magmatic bodies.

Types of Magmas. The Differentiation of Magma. The fact that the emergence of magmatic sources at various depths and in different thermodynamic conditions and the composition of original substance subjected to refusion is essentially possible, as well as the great diversity of magmatic rocks found in the earth's crust, quite naturally brings forth the question concerning the types of parent magmas.

There is no single opinion on this subject in geological sciences. Some researchers (V. Lodochnikov) consider that groups of magmatic rocks of different chemical content must be correlated with magmas of the corresponding composition. According to the views held by others (N. Bowen, A. Zavaritsky, and others) nature knows only the parent magma of basic composition (basaltic).

At present, however, the vast majority of geologists, following F. Levinson-Lessing, adhere to the assumption that there exist two kinds of parent magma, viz. the basic (basaltic) magma, the sources of which are formed within the confines of the upper mantle, and the acid (granitic) magma, characterized by intercrustal origin.

This viewpoint is substantiated by the fact that there is a marked predominance of granitic and basaltic rocks in the composition of the earth's crust, as well as the recurrence of particular associations of magmatic rocks in various parts of the earth's crust, which shows that they have common origin and were formed from one and the same source.

However, during the whole period in which a magmatic source exists parent magma experiences the most complicated physicochemical changes called *differentiation. Magmatic differentiation* can be defied as a combination of physicochemical processes that lead to the formation of rocks of different composition from the same magmatic melt. It can take place in a liquid magmatic melt as well as in the process of its crystallization. In this connection two main types of differentiation are singled out, viz. the magmatic and crystallization varieties.

Magmatic differentiation occurs prior to crystallization, i. e. as early as in the liquid magmatic melt, within the confines of magmatic sources or on the paths traversed by magma. The principal physicochemical factor which becomes responsible for the division of magma into individual fractions is considered to be *liquation*, or the segregation of the single homogenic magmatic melt into two non-mixing liquids, which differ from each other in their composition. Liquation is usually caused as a result of a gradual drop in magma temperature, though it can also lead to the assimilation of enclosing rocks through fusion, which results in the alteration of its composition.

The process involving the differentiation of magma in its liquid state is confirmed by the observations in the regions of recent volcanic activity. Thus, it is not infrequent that in the process of volcanic eruptions the lavas of acid composition are replaced by medium and even basaltic varieties. With some of the volcanoes in Kamchatka there were cases when intermediate and even acid lavas were erupted from the central vent, while basic lavas issued from the subordinate vents.

Crystallization differentiation is already connected with the process of crystallization of magma and accompanies it. During solidification of magma as the crystallization temperatures of the main rock-forming silicates are achieved, the crystals of the most refractory minerals, and olivine, in particular, fall out of the melt. They are followed by pyroxenes, which, in their turn, are simultaneous with or prior to the crystallization of basic plagioclases, to be succeeded by the same process involving medium and acid plagioclases, orthoclases, micas and, finally, quartz.

The ferromagnesian silicates that are the first ones to fall out of the melt owing to their relatively high density are subsided into the benthonic horizons of the magmatic reservoir, as a result of which the upper parts of the magma are constantly becoming poorer in such components as iron, magnesium, and calcium. They become remarkable for excess of silica and the degree of acidity is risen. Hence, besides the succession in which the minerals fall out in the process of crystallization differentiation, no minor role should be attributed to gravitational phenomena.

The most remarkable evidence of this natural process finds its expression in the differentiated (laminated) intrusions that have been described in many parts of the world. In the USSR such intrusions of basic and ultrabasic composition are widely spread in the north-western Siberian platform and in the Kola Peninsula, where the deposits of sulphide copper and nickel ores are connected with them. But this does not terminate the evolution of the magmatic chamber. The final stages in the crystallization of magma are known to be connected with pegmatites. According to A. Fersman pegmatites are formed from the residual silicate melts enriched with volatile components. The latter make these melts more mobile, which results in that pegmatites usually occur in the upper (apical) parts of parent intrusives or in their proximity in roof rocks where pegmatitic melts are penetrated along tectonic fissures. However, there also exist other opinions on the formation of pegmatites. A. Zavaritsky, for instance, says that their formation is accounted for by the change and recrystallization of rocks under the impact of gaseous solutions. Pegmatites can be associated with

Classification of Magmatogenic Processes of Mineral Formation

Process	Means and medium of mineralization	Productivity, %	Minerals (examples)
Magmatic proper	Minerals are crystallized directly from magma	8	Olivine, pyroxenes, hornblende, plagioclases, nepheline, apatite, chromite, magnetite, pentlandite
Pegmatitic	Minerals are crystallized from residual magmatic melts enriched with volatile components	10	Orthoclases, quartz, muscovite, lepidolite, topaz, beryl
Pneumatolytic and hydrothermal	Minerals are crystallized from gaseous and liquid solutions separating from magma	28	Wolframite, cassiterite, molybdenite, pyrite, galena, sphalerite, chalcopyrite, cinnabar, antimonite, bornite, barite, calcite, dolomite, fluorite

magmas of any composition, though the most widely spread and practically important pegmatites are those of acid magmas, or granitic pegmatites.

In the period of the solidification and crystallization of magma as well as within the time that follows them any intrusive becomes immediately connected with geological processes that are called *postmagmatic.*

At a certain stage of evolution of magmatic melt, when the solubility limit of volatile components is exceeded in it, *gaseous (pneumatolytic) solutions* in the form of an independent phase are separated from it, in which the main role is played by water vapours. When the temperature of the solutions drops to 450-400 °C they are transformed into *liquid,* or *hydrothermal* solutions. Pneumatolytic and hydrothermal solutions often evacuate a considerable amount of nonferrous, rare, noble and radioactive contained in the initial magmatic melt, thus forming deposits of mineral resources, which in many cases are of great industrial importance.

Throughout all the stages of the development of magmatic processes definite associations of minerals corresponding to particular conditions are formed. The processes of mineral formation connected with magma are classified according to the principal stages in the evolution of magmatic melts (Table 8).

The analysis of the data given in the table enables us to infer that the productivity of the processes of magmatism in the formation of minerals (the relationship of the number of minerals formed in the given process to the total number of mineral species in the earth's crust expressed as a percentage) is fairly great. Approximately 46% of the mineral species found in the earth's crust owe their origin precisely to the processes discussed below.

Magmatic Rocks

The processes of magmatism are mainly responsible for the emergence of magmatic rocks, which are formed from natural silicate melts by means of their crystallization or solidification at cooling.

They are the most widely spread rocks of the earth's crust, which enter into the composition of more than 60% of its volume and about 95% of its mass. Magmatic rocks are extremely varied in their mineral and chemical content, structure, forms and attitude in the earth's crust.

The material composition of magmatic rocks, i. e. their mineral and chemical compositions are closely related.

The main characteristic feature of their mineral composition is that all *the main rock-forming minerals* of magmatic rocks belong to *the class of silicates and alumosilicates.* They include feldspars (orthoclase and lime-soda – plagioclases), quartz, pyroxenes, amphiboles, olivine, micas, and feldspathoids. The most essential component of effusive rocks is also volcanic glass, which emerges during the rapid cooling of magmatic melts in surface conditions. On the whole the main rock-forming minerals account for 90-95% of the composition of rocks, in addition to which the average composition of feldspars is 65, pyroxenes and amphiboles – 15, quartz – 10.5, and micas 3.5%.

According to the chemical composition of the main rock-forming minerals two particular groups are clearly distinguished. Each of them has acquired a special term. The first group comprises magnesium-ferrous silicates, which are also called *femic.* This group includes olivine, pyroxenes, amphiboles, and biotite. The second group consists of calcium-alkaline or *salic* silicates and alumosilicates – feldspars, quartz, and feldspathoids.

Most of the minerals of the first group are characterized by dark shades of colour, as a result of which they are also referred to as *dark-coloured,* or *coloured minerals,* whereas salic minerals, which usually have light shades of colour, are called *light-coloured minerals.*

For different types of rocks the content of minerals belonging to the above-mentioned groups is markedly varied. If in the composition of rocks there is a predominance of colour minerals, the rocks also have dark shades of colour and are called *melanocratic* (dunite, pyroxenite, peridotite, etc.). In contradistinction to this the rocks consisting mainly of light-coloured minerals, are called *leucocratic* (granite, liparite, quartz-porphyry, and others). The intermediate types of rocks with approximately equal compositions of colour and light minerals can be called *mesocratic* (diorite, trachyte, and others).

The accessory minerals of magmatic rocks are represented by apatite, magnetite, zircon, ilmenite, tourmaline and muscovite (the two preceding minerals in some types of rocks can be transferred into the class of the main ones).

Secondary minerals, which are the disintegration products of main minerals in the processes of the secondary change of rocks, are represented by chlorite, serpentine, epidote, kaolinite, carbonates, and others. In markedly altered magmatic rocks their quantities can be fairly great.

Magmatic rocks are regular associations of minerals rather than their mixtures that occur by chance. The presence of a certain rock-forming mineral in

the rock most necessarily leads to the appearance of some minerals, and, conversely, to the absence of others. The rock-forming minerals show the chemical properties of any rock. For instance, the presence of quartz provides the evidence of silicon in the original melt; the presence of nepheline, however, serves to prove the lack of silica. The content of dark-coloured minerals is regularly changed in various types of magmatic rocks. Thus, in rocks that are so rich in silica, that allow the presence of free quartz in them, the content of dark-coloured minerals does not exceed 20%, while in rocks, containing less than 50% of silica, the content of dark-coloured minerals is increased up to 40-50% and more.

The variety of the chemical composition of magmatic rocks corresponds to the diversity of their mineral content. Since the majority of them are composed of silicates, the most important components, as far as the chemical composition is concerned, are those that enter into the composition of silicates. In decreasing order of the quantitative role played by them they are: SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, CaO, Na_2O, K_2O, and H_2O. The accessory chemical components are MnO, TiO_2, ZrO_2, Cr_2O_3 and others. Besides, for the purpose of classifying magmatic rocks according to their chemical composition the content of SiO_2, which is the most important component, or the degree of the acidity of rocks, must necessarily be taken into account.

Composition. The textures and structures of magmatic rocks chiefly depend on the conditions of their formation.

In the process involving the origin of intrusive bodies, when the cooling of magma takes place at a certain depth and there are no marked changes in temperature and pressure, the uninterrupted crystallization of the melt occurs in most quiet conditions. Hence, all intrusive rocks possess *holocrystalline structures*, i. e. they consist of crystalline grains of various minerals. In addition to this, the abyssal rocks are characterized by holocrystalline *equigranular* textures, while *inequigranular textures* are typical of the hypabyssal rocks. Those of the latter that are most widely spread are *the porphyraceous texture*, when relatively large impregnations of a certain minerals are developed against the background of the more microcrystalline basic mass, and the *pegmatitic texture*, distinguished by a very close reciprocal intergrowth of (graphitic) quartz and feldspar. Depending on the size of the crystalline grains of minerals holocrystalline structures are divided into coarse-, medium-, and fine-grained varieties, with the size of grains measuring more than 5, from 5 to 2, and less than 2 mm, respectively.

In the formation of effusive rocks as a result of the outflow of magmatic melts in the form of lava onto the surface of the earth, there occurs a marked change in thermodynamic conditions, which disrupts the calm crystallization of the melt and leads to its rapid solidification. This results in that there emerge textures that refer to those of the *hypocrystalline* type, when alongside the crystalline grains of minerals the rock becomes invariably remarkable for the presence of a certain amount of volcanic glass. Depending on the degree of crystallinity among the hypocrystalline structures the following macrostructures can be singled out: *the vitreous* variety (the rock is not crystallized, *the aphanitic* type (the cryptocrystalline one; the finest crystals can be observed only with a microscope), and the *porphyritic* type, when against the background of vitreous or cryptocrystalline

main mass in the rock we can find crystals (porhyritic separations) of certain minerals.

The main types of structures of intrusive magmatic rocks are *the massive* ones, or those that are dense, compact, and with the irregular distribution of mineral grains.

The effusive rocks are to a greater degree characterized by *porous* and *vesicular* structures, which emerge as a result of the evacuation of volatile substances from lava. In due course the voids can be filled by a mineral substance, and then the structure is referred to as *amygdaloidal*. When the features of lava movements are preserved in the form of regular orientation of mineral grains there appear the so-called *fluidal* structures. The most important types of structures and textures of magmatic rocks are given in Fig. 56.

The forms of occurrence of magmatic rocks are extremely varied, particularly in the case of intrusive rocks. It is not infrequent that in field-work conditions the forms of occurrence help to establish the affinity of a rock to a certain genetic group.

The forms of occurrence that are most characteristic of effusive rocks are lava *streams* and *sheets*.

The intrusive rocks formed at considerable depths (the abyssal type) are remarkable for the most widely spread forms of geological bodies called batholiths and stocks. Hypabyssal intrusive rocks are characterized by less prominent dimensions of geological bodies, though their morphology is highly

FIGURE 56. The most widespread textures and structures of magmatic rocks. Macrotextures: *a* – equigranular; *b* – pegmatitic; *c* – porphyroid; *d* – vitreous; *e* – porphyritic. Structures: *f* – massive; *g* – banded; *h* – taxitic

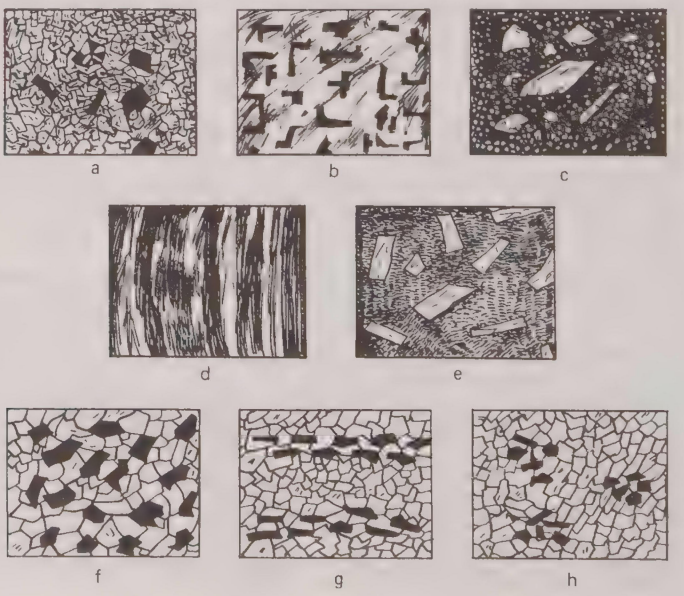


TABLE 9. Classification of Magmatic Rocks

Chemical type of rock (SiO_2 content, %)	Intrusive rocks		Effusive rocks		Principal rock-forming minerals
	abyssal	hypabyssal	cenotypal	paleotypal	
Ultrabasic (> 45%), markedly undersaturated with silica	Dunite, peridotite, pyroxenite, hornblendite	–	Kimberlite		Olivine, pyroxenes (less often hornblende and biotite)
Basic (45-52%), oversaturated with silica	Gabbro	Gabbro-porphyrite, diabase	Basalt	Basaltic porphyrite	Basic plagioclases, pyroxene (less often olivine, biotite, hornblende)
Medium (52-65%), saturated with silica	Diorite	Diorite-porphyrite	Andesite	Andesite porphyrite	Medium plagioclases, orthoclase, hornblende, less often micas
	Syenite	Syenite-porphyrite	Trachyte	Trachyte-porphyrite	Orthoclase, acid plagioclase, micas, amphiboles
Acid (> 65%), oversiliconized	Granite	Granite-porphyry Aplite Pegmatite	Liparite (rhyolite)	Liparite-porphyry (quartz-porphyry)	Quartz, acid plagioclases, orthoclase, biotite (less often muscovite, hornblende, pyroxenes)
	Granodiorite	Granodiorite-porphyry	Dacite	Dacite-porphyrite	
Alkaline (about 55%) high content of K_2O, Na_2O	Nepheline-syenite	Nepheline-syenite porphyry and pegmatites	Phonolite	Phonolite-porphyry	Orthoclase, nepheline, alkaline pyroxenes and amphiboles

TABLE 10 The Extent (%) of the Most Important Types of Igneous Rocks on the Territory of the Soviet Union and the USA (According to A. Zavaritsky)

Types of rocks	USSR	USA
Acid intrusions	48.7	35.0
Basic intrusions	2.3	5.0
Acid effusions	13.5	12.5
Basic effusions	35.1	45.0
Alkaline rocks	0.4	—

varied. Concordant bodies which are most often found have the forms of laccoliths, lopoliths, phacoliths, sills, and those that intersect in the form of dikes, veins, and necks.

The Classification of Magmatic Rocks. There are two basic principles that underlie the classification of magmatic rocks. They are: (1) *the genetic principle*, and (2) *the principle of chemical composition* (Table 9).

The Distribution of Magmatic Rocks and Factors Conditioning Their Variability. At present there is a lack of any comprehensive data concerning the distribution of various types of magmatic rocks within the confines of the whole world. However, on the territory of the two largest countries the areas where different magmatic rocks occur have been estimated (Table 10).

According to the data provided by A. Ronov and A. Yaroshevsky, granites occupy 10.4% of the volume of the earth's crust, granodiorites and diorites - 11.2, basalts, gabbro and other rocks of the basic composition - 42.5, syenites and nepheline syenites 0.4, dunites and peridotites - 0.2%. From the data that have been adduced it is possible to derive the information on the maximum distribution of magmatic rocks of acid and basic composition. It should be mentioned that among the acid rocks the intrusive varieties (granites and granodiorites) are the ones that are most widely developed, while effusive varieties (basalts) are most typical of the basic rocks.

Nowadays the main factor conditioning the variability of magmatic rocks is attributed to *the differentiation* of parent magma. Magmatic and crystallization differentiation leads to the division of the original melt into fractions that are distinguished from each other according to chemical composition, which results in that the formation of chemically diverse rocks out of the common magmatic chamber becomes virtually possible.

The other factor that accounts for the change in the composition of parent magmas, and, consequently, the variety of igneous rocks is associated with the processes of *assimilation* and *hybridism*, i. .e. a complete or partial absorption and refusion of inclusions (xenoliths) by the magma into which it is intruded. However, the prevalence and the scales of these phenomena have not yet been given all the attention they deserve.

The Jointing of Magmatic Rocks. During the cooling and crystallization of magmatic melts from which magmatic rocks are formed, there appear fissures that are better known as *joints*. These fissures break the rocks into separate blocks.

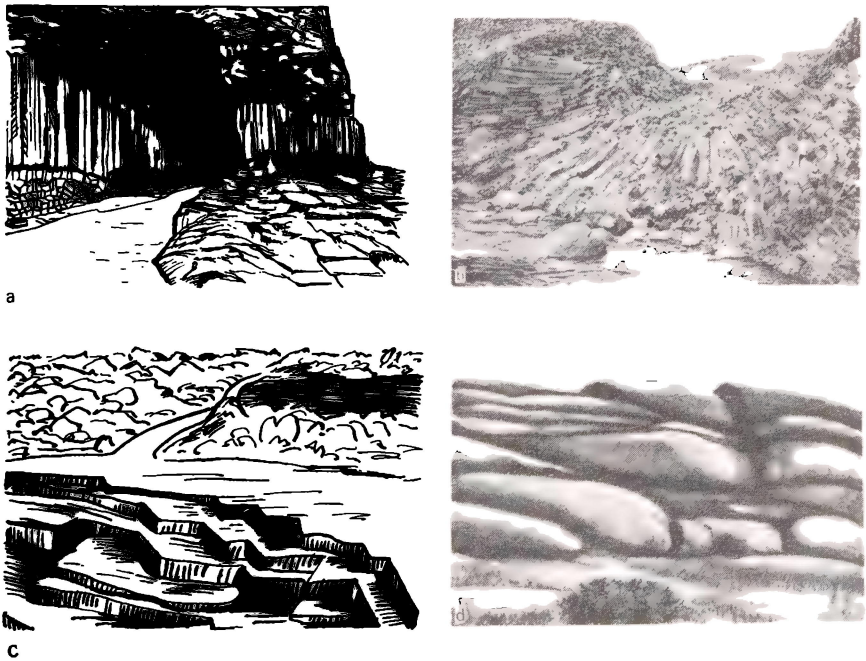
Effusive magmatic rocks are chiefly characterized by *columnar* jointing, formed as a result of compression in the course of rapid cooling, which begins from the surface of lava. Incidentally, the rocks are divided into blocks, which have the form of columns with hexagonal or pentagonal sections, closely connected with each other and oriented perpendicular to the surface of cooling. This is what accounts for the fact that with horizontally occurring streams the beds are situated vertically. In most cases columnar jointing is found in sheet intrusive deposits of andesitic and basaltic composition.

The submarine outflows of basaltic lavas often give rise to *spheroidal* jointing, when the concentrically arranged fissures divide the rock into spheres with the diameter from some centimetres to several metres. In dikes and sills spheroidal or globular varieties of jointing can be developed in large blocks, situated within the interstices between the neighbouring fissures of main jointings. The blocks between them become subjected to cracking along the concentric surfaces.

In effusive rocks, which undergo the influence of tectonic factors when the stage of cooling is reached, in addition to original joints there can appear those of the secondary type. With respect to the original joints they are most often oriented approximately at an angle of 45°.

In intrusive magmatic rocks joints are the result of the interaction between compression sills during the cooling and crystallization of magmas and the tectonic stress that comes next.

FIGURE 57. The jointing of magmatic rocks:
a columnar vertical variety of jointing in basalts; *b* – fan-like variety of jointing in basalts; *c* – slab parting in granites; *d* – hammock jointing in granites



In large magmatic bodies, particularly of granitic composition, it is *the platy* jointing that becomes most apparently manifested, i. e. when the fissures dissect the rock into blocks, that often have pillow-like and tubular form.

In the central part of massifs this kind of jointing is very much the same as that of horizontal variety, while in the marginal areas it acquires an inclined position with the dip towards the zone of contacts.

Besides, in the case of tectonic stresses there emerge in intrusive massifs steeply dipping longitudinal, transverse and diagonal fissures, which are regularly situated with respect to pressure forces.

The systems of fissures described above break the massif into blocks, which have the form of parallelepipeds. Some types of jointing of magmatic rocks are shown in Fig. 57.

It is necessary to take into consideration the presence of joints in magmatic rocks when mining and construction works are conducted. For instance, in the exploitation of construction stone the presence of jointing considerably facilitates the operations, though at the same time it often hinders the production of monolithic blocks of large dimensions. When explosives are used, the presence of fissures becomes responsible for the emergence of additional paths along which gases are propagated, as a result of which the power of explosion can be markedly reduced.

In the building of hydrotechnical structures joints can lead to a great loss of water when it is filtrated through them.

Role of Magmatism in the Formation of Mineral Deposits

The processes of magmatism, particularly those of the intrusive type, are highly productive as far as the formation of mineral resources is concerned. All the deposits the formation of which is connected with the activity of magma are called *magmatogenic*. Mineral deposits can practically be created in all the stages of the evolution of magmatic melts.

During crystallization of magmatic melt magmatic deposits are formed. They are usually connected with magmas, and, consequently, with rocks of ultrabasic, basic, and alkaline composition. This can be illustrated by the deposits of chromites, diamonds, titanomagnetite, sulphide copper and nickel ores, metals of the platinum group, as well as the deposits of apatites, which are widely employed for the production of phosphorus fertilizers, and nepheline syenites, where nepheline is at present used for the extraction of aluminium.

The crystallization stage of magmatic melts that are rich in volatile components coincides with the formation of pegmatite deposits of such important mineral resources as mica (muscovite), precious stones, tin, tungsten, molybdenum, lithium, beryllium, uranium, thorite, tantalum, niobium, and others.

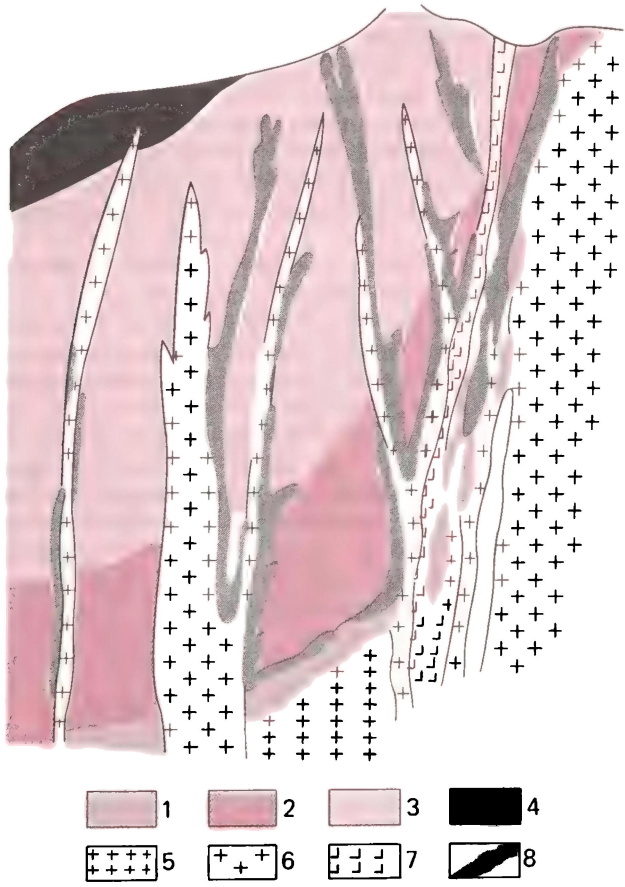
The formation of important deposits of a large number of mineral resources is connected with the activity of hydrothermal solutions. They are the deposits of copper, gold, silver, lead, zinc, mercury, antimony, molybdenum, tungsten, uranium, etc. Most of the hydrothermal deposits have a veined form.

The processes that develop in the near contact zones of intrusives are characterized by the formation of iron, copper, lead, and zinc, as well as tungsten and molybdenum ore deposits.

The forms of ore bodies of magmatogenic deposits are exceptionally varied and often highly complicated (Fig. 58). This is exemplified by veined bodies, pockets, stockworks, pipes, and less often by tabular and lenticular deposits. The specific feature of a large number of magmatogenic deposits is also the complexity of ores and the complicated character of their mineral and chemical compositions.

The morphological diversity and the complicated character pertinent to the bodies of mineral resources as well as the complexity of the composition of ores

FIGURE 58. Form of orebodies of post-magmatogenic deposits. Altyn-Topkan skarn deposit (according to A. Amiraslanov):
1 – effusive and sedimentary rocks; *2* – dolomites; *3* – limestones; *4* – tuffs; *5* – granodiorites; *6* – granodiorite-porphyries; *7* – granite-porphyries; skarn and orebodies



are necessarily taken into account when choosing the technological schemes for the development and reworking of mineral raw-materials that are recovered from the deposits of magmatogenic origin.

In conclusion, it should be mentioned that the magmatic rocks themselves are widely used as pieces of building stone, the material for manufacturing high-quality paving blocks, slabs, and facing stones in cement and stone-foundry industry.

Chapter 11 Metamorphism. Metamorphic Rocks

The term 'metamorphism' has been firmly established in geological studies since 1825 when it was introduced by Ch. Lyell.

The term *metamorphism* covers the alteration and transformation of rocks under the influence of various endogenic geological processes which bring about considerable changes in thermodynamic conditions (first and foremost, temperature and pressure). In other words, the essence of this process consists in the accommodation of rocks to the environmental thermodynamic conditions that are distinct from those under which they were formed.

All the transformations undergone by rocks within the process of metamorphism are brought about through their recrystallization in a solid state, i. e. without any remelting. It is only in some very rare cases that at considerable depths metamorphism can be accompanied by a partial or complete remelting of rocks.

Metamorphism can exercise its impact upon rocks of any origin. This is equally the case with sedimentary and magmatic rocks, as well as with the metamorphic ones that existed before. It is quite natural that those that lead themselves to metamorphism most readily are the rocks the formation of which is to a greater extent distinguished from the physicochemical circumstances that exist under metamorphism.

Metamorphism is characterized by changes in the structural and textural peculiarities of rocks and their mineral composition as a result of the replacement of old mineral associations by the new ones, i. e. those that are stable in the newly created thermodynamic conditions. In a number of cases we also find a change in the chemical content of rocks. The degree of primary rocks changes, i. e. the degree of metamorphism, can be quite different, ranging from insignificant transormations to a complete change of the composition and shape of rocks.

Basic Factors of Metamorphism

The main reasons, or factors, conditioning the metamorphism of rocks are temperature, pressure, and chemically active substances – solutions and volatile compounds.

Temperature. According to the opinion of the vast majority of scientists, the processes of metamorphism occur within the temperature range from 250-300 to

800 °C. The rise in temperature by only 10° enhances the rate of chemical reactions twice, while by 100° it increases one thousand times. In conditions of the earth's crust the rise in temperature is caused by two main reasons: (1) the subsidence of rocks to greater depths, which leads to the growth in temperature owing to geothermal gradient (1° per 33 m on average); (2) the thermal impact of magmatic melts intruding into the earth's crust. The rise in temperature can also be conditioned by the inflow of deep-seated fluids, local development of internal heat flow, and several other factors.

Pressure can be either *petrostatic* (all-round) or *lateral* (unilateral), which is known as *stress.*

Petrostatic pressure is the function of the depth and its growth is usually associated with the subsidence of rocks into the deeper regions of the lithosphere.

The relationship between depth and pressure are approximately estimated by the following figures: the increase in depth per 3 km corresponds to the growth of pressure per 100 MPa. If we consider that the processes of metamorphism are most prominently developed at the depths from 10 to 50 km, the petrostatic pressure in these conditions must be equal to about 400-1 500 MPa. The growth of petrostatic pressure becomes mainly responsible for the change in the volume of rocks and promotes the formation of minerals characterized by great densities and small specific volumes.

Petrostatic pressure also raises the temperature of melting point of minerals, thus expanding the temperature range of transformations in the solid phase. The all-round pressure usually serves as a favourable factor in the formation of rocks the structures of which are homogeneous.

Lateral stress emerges in the course of intense tectonic movements of dislocation character. It leads to the deformation of minerals, causes the appearance of their regular spatial orientation in rocks. Thus, for instance, platy minerals are arranged with the cleavage planes directed perpendicularly towards the direction of pressure, as a result of which the so-called foliated structures of rocks are formed. In a number of cases bringing about the crushing of rocks, the stress increases their filtration properties, thus giving impetus to the circulation of metamorphosing solutions.

The oriented stress is most prominently manifested in the upper horizons of the earth's crust, where the load of the overlying rocks is inconsiderable. With the growth of depth and petrostatic pressure the role of stress becomes gradually diminished.

The chemically active substances (water, carbon dioxide, hydrogen, the compounds of chlorine, sulphur, etc.) are the catalysts, which facilitate the reactions between crystals, take part in the formation of new minerals by entering into their textures and replacing the old mineral associations by new ones.

According to the views held by the Soviet scientists D. Korzhinsky, V. Zharikov, A. Marakushev and others, metamorphosing solutions are of abyssal (subcrustal) origin. Diffusing from the depths of the Earth through the voids of rocks and magmatic melts and enriched on their way of movement with various mineralizers, they become transformed into active agents of metamorphism. The

other sources of solutions are magmatic melts separating them on definite stages of evolution.

A substantial role in metamorphism is attributed to *time factor* since all these processes are very long and occur within the span of geological time. However, it would be erroneous to assume that the age of rocks is directly correlated with the degree of metamorphism. It has already been made abundantly clear that everything depends entirely on the concrete geological situation. The fact is that the manifestations of the internal energy of the Earth (magmatism and considerable subsidences of the earth's crust, which are accompanied by powerful sedimentation, folded and faulted disturbances), which are the main factors accounting for metamorphism, are confined to the mobile zones of the earth's crust, or geosynclinal regions. Hence, it is quite natural that the phenomena of metamorphism are also spatially connected in the main with these areas. In undisturbed geological conditions, within the confines of platforms, even the most ancient rocks have remained intact as far as the processes of metamorphism are concerned.

The transformation of rocks in the course of metamorphism can be of quite different character. In those cases when there is an absence of addition and loss of components the chemical composition of rocks remains practically unchanged (for instance, the transformation of limestone into marble). This kind of metamorphism is called *normal*, or *isochemical*. If, however, metamorphic transformations are accompanied by a marked addition and loss of substances, there takes place the replacement of certain types of mineral association by others, and the chemical composition of rocks is altered. The metamorphism in question is referred to as that of *metasomatic* variety.

Types of Metamorphism

The processes of metamorphism are very complicated, varied and can often be conditioned by the synchronous activity of all basic factors. However, according to the predominant role in the process of some factors, as well as the dependance on the scope within which the phenomena of metamorphism are developed in space certain kinds or types of metamorphism are singled out. The main types of metamorphism are: regional, contact varieties, and dynamometamorphism. In accordance with the characteristic features of the process that takes place in each type certain variations can be singled out.

Regional metamorphism is the most widespread and significant type of metamorphism, since it covers extensive areas and whole regions. It is manifested in conditions when individual parts of the earth's crust undergo a continuous progressive subsidence, as a result of which rocks are displaced from the upper horizons of the earth's crust into the deeper ones. As a rule, warping is compensated by sedimentation, and thus the main factors of regional metamorphism find their expression in petrostatic pressure and temperature, the gradual rise of which is conditioned by geothermal gradient; an essential function is also shared by unilateral (side) stress and chemically active substances.

Since conditions of this kind are usually expressed in tectonically mobile parts of the earth's crust, it is precisely within the confines of geosynclines of different

age that the processes of regional metamorphism are manifested. Rocks that have undergone marked changes in the processes of regional metamorphism are developed in the basements of ancient platforms and the area where the basement comes out onto the surface is called *shields*.

The opinion that the warping of the earth's crust is in itself responsible for metamorphism has continually failed to receive any coherent acknowledgement in geological sciences over the past few decades. Within the limits of some large depressions (for instance, in the Caspian Sea region), where there is no evidence of dislocation tectonic movements, sedimentary rocks are practically non-metamorphosed. Apparently, the development of the processes of regional metamorphism should be associated with definite stages in the evolution of the earth's crust, characterized by intense folding, the elevation of magmatic masses and the thermal solutions connected with them.

The extent to which rocks are altered under regional metamorphism is directly related to the degree involving the change of environmental thermodynamic conditions. A number of scientists (U. Grubenmann, N. Lukashevich, and others) regard the depth at which the process takes place to be the main criterion of the change in conditions, since it is precisely what essentially determines pressure and temperature. In compliance with this, several zones of regional metamorphism characterized by various degrees of the alteration of rocks are distinguished.

Epizone (the upper zone) is characterized by moderate temperature and petrostatic pressure, which can be superimposed by a strong unilateral stress. In these conditions there emerge phyllites, chlorite, and talc schists.

Mesozone (the middle zone) is situated at a great depth and is remarkable for high temperature and pressure (petrostatic and unilateral). Under these circumstances, the complete recrystallization and intense schist-forming process of rocks take place. There appear mica schists, amphibolites, gneisses, marbles, and quartzites.

Catazone (the lower zone) is distinguished by high temperature and petrostatic pressure, in connection with which the function of unilateral stress is not of any great significance. The schistosity is expressed but poorly, and there occur such rocks as pyroxene, biotite and sillimanite gneisses, eclogites, quartzites, and some others.

A still greater increase in depth can result in the growth of temperatures and pressures up to the values that are sufficient for a partial or complete melting of original rocks. Therefore, in the deeper regions of the earth's crust a particular stage of regional metamorphism known as *ultrametamorphism* can become evident. The terms employed to designate partial and complete melting are *anatexis* and *palingenesis*, respectively. Melts, that emerge in the process of ultrametamorphism and which are usually characterized by a granitic composition, penetrate into the enclosing rocks, pierce them and thus form peculiar rocks of a mixed composition called *migmatites*. Migmatites are widely developed within the confines of the ancient Baltic, Ukrainian, and Aldan shields.

Ultrametamorphism is often associated with the phenomena of granitization, which consist in the metamorphic change of rocks of any composition with their subsequent transformation into granites. Incidentally, the original rock most

necessarily passes through the stage of magmatic melt. The principal agents of granitization are considered to be the fluids supplied from great depths. Thus, in the conditions characterized by most prominent metamorphic transformations, to which ultrametamorphism belongs, the borderline between magmatic and metamorphic processes becomes practically blurred.

The ever-growing amount of factual material has made it clear that the rule concerning the dependence of the degree of metamorphism from the depth has quite a few exceptions to it, and that the rocks characterized by approximately the same degree of metamorphism can be found at quite different depths. This is conditioned by a large number of factors which in every particular case influence the metamorphic processes: the different value of geothermal gradient, dislocation tectonic movements, resulting in the growth of lateral stress, etc.

That is why at present, when discussing zones of metamorphism one takes into account the sum of physicochemical conditions that are created at a certain depth. In accordance with it most of the scientists (P. Escola, D. Korzhinsky, A. Marakushev, V. Sobolev, and others) employ the concept of metamorphic facies for the characterization of processes of metamorphism and the classification of metamorphic rocks.

The metamorphic facies is taken to be a group of rocks of different composition, which were formed in similar thermodynamic conditions. These conditions are indicated by the so-called index-minerals, which are characterized by their stability in particular conditions of temperature and pressure. Thus, the presence of certain mineral associations is found to be typical of every zone of metamorphism.

Up till now when discussing the phenomena of regional metamorphism what we had in mind were the processes that occur during the growth of temperature and pressure, or the so-called progressive metamorphism. But one can also discover processes in nature that are opposite to progressive metamorphism, i. e. when rocks that were formed at high temperatures and pressures can occur in different thermodynamic conditions, as a result of ascending tectonic movements. In cases like these there emerge mineral associations of lower temperature, new and stable under the given circumstances, which are superimposed on the ones that existed before. These processes are called *regressive metamorphism*, or *diaphthoresis*. Other types of metamorphism, as distinct from its regional variety, have but a local character.

Contact metamorphism is manifested at the contacts of magmatic melts that are intruded into the earth's crust together with the enclosing rocks. In the proximity of the contact an aureole of metamorphic rocks is formed, which usually covers the rocks surrounding the magmatic body (*exocontact metamorphism*), as well as the marginal parts of the magmatic body itself (*endocontact metamorphism*). The width of the zone of contact change (contact aureole) can vary from centimetres to the first kilometres depending on the size and composition of magmatic bodies, the depth of their intrusion, the physicomechanical properties and the chemical activity of enclosing rocks. The zones of contact metamorphism are given in Fig. 59.

The main reasons accounting for the change of rocks in the zones of contacts, or the basic factors of contact metamorphism, are temperature, which acquires

greater values owing to the heat action of magmatic masses upon the enclosing rocks, and the chemically active gaseous and liquid solutions released by the magmatic melts. In this case, the role of pressure is regarded as that of secondary importance. In accordance with the specific features of the process several varieties of contact metamorphism are distinguished.

Thermocontact metamorphism finds its expression in a purely thermal impact of magma upon the enclosing rocks, which leads to recrystallization, the formation of new minerals, but is not accompanied by any change of the total chemical composition.

Rocks that emerge under these processes at the expense of clay and sandy-clay sediments are usually characterized by compact fine-grained structure and are called hornfelses. Limestones are transformed into marbles, quartz sandstones likewise become quartzites, etc.

A special variety of thermocontact metamorphism comprises *pyrometamorphism*, which is in most cases expressed in the burning and baking of rocks under the influence of lavas. Contact changes of this kind cover zones the range of which is not more than several centimetres.

In the case of *contact and metasomatic metamorphism* the impact upon the enclosing rocks of gaseous and liquid mineralized solutions emitted by them combines with the temperature influence of the intrusive in the state of congelation. Between solutions and enclosing rocks there take place various chemical reactions accompanied by the influx and evacuation of individual components, and thus the process, in contrast to thermocontact metamorphism, proceeds with a change of the chemical composition. The said process involving the replacement of one kind of minerals by others, which presupposes the activity of gaseous and liquid solutions and is simultaneous with the change that occurs in the chemical composition of mineral formations is called *metasomatism*, while the rocks that are formed in these conditions are referred to as *metasomatites*. Depending on the aggregate state of the solutions pneumatolytic and hydrothermal varieties of metasomatic metamorphism are distinguished. The most widespread contact and metasomatic rocks are skarns and greisens.

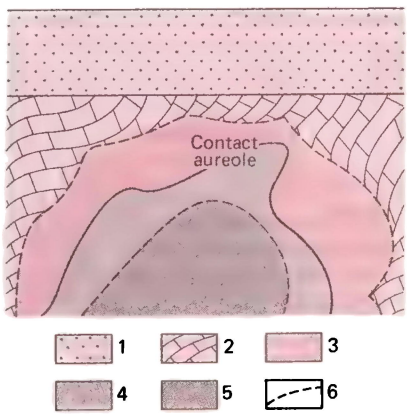


FIGURE 59. Zones of contact metamorphism:

1, *2* – unaltered enclosing sedimentary rocks; *3* – metamorphized rocks of exocontact zone; *4* – metamorphized rocks of endocontact zone; *5* – unaltered granites; *6* – boundary of contact aureole

Among the pneumatolytic and hydrothermal processes connected with metamorphism the group of autometamorphic processes is also singled out.

Autometamorphism is a process characterized by an alteration of igneous rocks in the course of their formation (solidification and crystallization) under the influence of chemically active components, that are emitted by the magma itself, as a result of temperature drop, etc. Residual solutions and gases cause metasomatic changes of minerals in the very massif of magmatic rocks. This is, for instance, how serpentinization of ultrabasic rocks, chloritization of basalts, greisenization of granites, etc., take place.

Dynamic metamorphism (cataclastic, dislocation metamorphism) is chiefly manifested in the upper parts of the earth's crust, and in the zones of tectonic movements of dislocation character. They are often localized along the tectonic dislocations with a break in continuity. Thus, *unilateral stress* may well be regarded as the main factor conditioning it. It is mainly the characteristic features of rocks that undergo textural and structural changes during the dynamic metamorphism. What takes place is their fracturing (cataclasis), while in the deeper zones as a result of temperature rise the mechanical disintegration is succeeded by plastic deformations. The banding that appears in rocks finds its expression in the alternation of layers with grains of different form and minerals that are likewise diverse in colour. All this is most closely connected with the emergence of crystalline schistosity.

Metamorphic Rocks

The formation of metamorphic rocks is the main geological result of metamorphism processes.

Composition. Of all the material components, the existence of which is possible in rocks, the composition of metamorphic rocks can include only mineral crystals. This is the consequence of their formation related to the recrystallization of any of the original (primary) rocks.

The chemical composition of metamorphic rocks is very complicated and varied, since they originate at the expense of different sedimentary, magmatic rocks as well as the metamorphic ones that existed before, and in a number of cases within the processes of their formation no minor function is shared by the influx and evacuation of chemical components.

The mineral composition of metamorphic rocks is characterized by the following basic peculiarities:

(1) it comprises almost all the main rock-forming minerals of igneous rocks, e. g. quartz, feldspars, pyroxenes, olivine, amphiboles, micas, and others;

(2) besides, newly formed minerals are established there. They are of metamorphic origin proper, and are considered to be specific indicators of these rocks. They include garnets, talc, chlorites, serpentine, disthene, sericite, epidote, wollastonite, etc.

Minerals that are inherited from parent rocks make up the group of *relic minerals*. Minerals emerging only in the processes of metamorphism are called *typomorphic minerals*. Associations of minerals that have appeared in given

thermodynamic conditions give rise to *the mineral facies* of metamorphic rocks (Fig. 60).

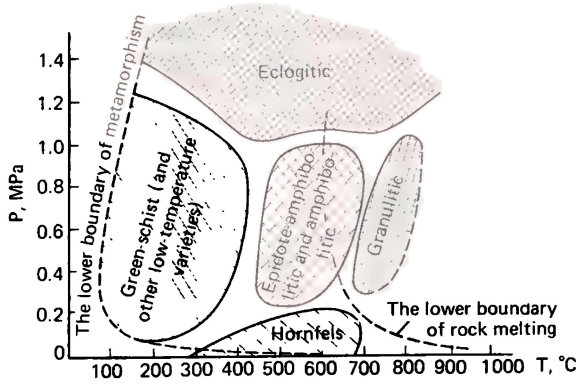
Mineral facies correspond to different stages of metamorphism, viz. the lowest, middle, and highest ones. *The facies of green schists*, for example, brings together rocks of the lowest stage of metamorphism, which includes clay, phyllite, green, siliceous and chloritic schists. They are also characterized by such typomorphic minerals as chlorite, actinolite, epidote, albite, serecite, and calcite. The most important (critical) mineral among them is actinolite.

The epidote-amphibolitic facies comprises rocks characterized by a higher degree of metamorphic changes. This includes crystalline schists, quartzites, marbles, and amphibolites. Typomorphic minerals are epidote, disthene, oligoclase, garnet (almandine), stavrolite, biotite, and hornblende. In carbonaceous rocks this facies is expressed by epidote, garnet (grossular), and vesuvianite, with epidote as the critical mineral.

The amphibolitic facies corresponds to the middle and high stages of metamorphism, and according to physicochemical conditions of formation is fairly close to the preceding facies. The rocks of amphibolitic facies, viz. gneisses, disthene-garnet-micaceous schists, amphibolites, quartzites, various rocks consisting of quartz, feldspars, garnet, disthene, hornblende and others are formed within a wide range of temperature and pressures. The typomorphic minerals of this facies are hornblende (of greater temperature than in the preceding facies), middle plagioclase, disthene, garnet (almandine and grossular), and stavrolite; in rocks that are situated near the upper boundary of the facies there appear sillimanite. The critical mineral here is hornblende.

The granulitic facies is connected with the highest stage of metamorphism. Rocks that belong to it are markedly altered (to the extent of partial refusion). They are represented by granulities, gneisses, and migmatites. The presence of high-temperature minerals – hypersthene, diopside, magnetite, rutile, spinel, sillimanite, cordierite, as well as garnet, amphibole, quartz, and plagioclases – is typical. Minerals containing constitutional water (muscovite and biotite) are absent.

FIGURE 60. Facies of metamorphism (the boundaries between facies are gradual)



The eclogitic facies occupies a very special place among other metamorphic facies. The rocks of this facies are characterized by basic or ultrabasic composition. Metamorphism gives rise to the formation of gabbro, peridotites, dunites, and amphibolites. The typical minerals are sodium-containing diopside, garnets (grossular and pyrope), as well as orthoclase, quartz, disthene, and rutile. Some scientists refer eclogites to magmatic rocks.

The hornfels facies is a typical facies of contact metamorphism and is represented by various hornfelses. The characteristic minerals are albite, biotite, epidote, andalusite, cordierite, diopside, and vesuvianite.

The Structure and Forms of Attitude. The textures and structures of metamorphic rocks are characterized by a great variety, which is conditioned by the peculiarities of their formation. First and foremost, it should be mentioned that all metamorphic rocks have *a crystalline structure.* However, their crystallinity differs in its origin from the crystallinity of magmatic rocks. If in the formation of igneous rocks mineral crystals are segregated from the silicate melt in a certain order, the growth of all minerals in the process of metamorphism takes place at one and the same time, and the solid state of the rock is preserved. The term *blastesis* is specially employed to denote the process of crystallization of minerals in a solid state. In this connection, the most characteristic structures of metamorphic rocks are *the crystalloblastic* ones.

Depending on the predominant form of mineral grains these structures can be classified as follows: *the granoblastic structures,* consisting of more or less isometric grains (granules), *the lepidoblastic structures,* in which mineral grains have a foliated, scale or platy form, *the nematoblastic structures,* characterized by acicular and prismatic forms of the removal of minerals, as well as *the porphyroblastic structures,* which emerge in those cases when individual minerals, owing to their great crystallization property, give rise to relatively prominent separations (porphyroblasts) within the mass of others. Individual types of structures can also be remarkable for mutual transitions, as is, for example, the case when autonomous development in a rock is shared by grains of isometric and flat form. The structure in instances like these can be called *lepidogranoblastic.*

The second structural type of metamorphic rocks is *the relict textures,* which are charcterized by the retention of the elements pertaining to the parent rock structure. Thus, in the structures of gneisses it is not infrequent that the structure of granite is preserved; in metamorphosed sandstones and schists we find the characteristic structural features of sedimentary rocks, in amphibolites (metamorphosed diabases), the remains of diabasic (ophitic) structure, etc. It has become common practice to form the names of relict structures by attaching the prefix 'blasto' to the term denoting the original rock texture, e. g. blastoporphyric, blastogranitic, blastophitic, etc.

Cataclastic textures are formed during the tectonic fracturing (cataclasm) of rocks. They are classified into *granoclastic* (equigranular), *porphyroclastic* (inequigranular), and *the cement textures,* when the rock retains large relicts of primary minerals confined within a finely crushed mass.

The structures of metamorphic rocks are divided into *relict* and *metamorphic* varieties. Relict textures are exemplified in those cases when a rock retains the

texture of original parent rock. Thus, in metamorphosed sedimentary rocks their lamination is often preserved. The characteristic feature of metamorphic structures is their *anisotropy*, which finds its expression in the subparallel orientation of elongated and flattened mineral grains, and conditioned by the directed influence of unilateral pressure upon the rocks, the plastic flow, and the anisotropism of the forces relevant to the growth of crystals. In the conditions of unilateral pressure favourable circumstances are created for the development of minerals elongated in one or two directions (prismatic, acicular, fibrous, platy, tabular, and foliated varieties), as well as their regular reorientation in rocks. This results in that the following main types of structures are formed: *the schistose structure* – when the orientation of platy or elongated grains is non-diversified; *the eutaxitic texture*, which is characterized by the isolation of monomineral acumulations in the form of bands; *the linear structure* in those instances when there is a linear isolation of individual minerals or their concentrations; *the plicated structure* – exemplified by the crumpling of mineral isolated associations into small folds; *the augen*, or *lenticular*, texture formed by the parallel-oriented lenticular concentrations of minerals, and several others. In some rocks, particularly of the contact and metamorphic variety, we have what is known as *massive structures*. The main types of structures and textures of metamorphic rocks are illustrated in Fig. 61.

One of the most important textural characteristic features of metamorphic rocks is their *cleavage*, i.e. the property of a rock to be split along the parallel planes of secondary origin. There are two types of cleavage: *the flow variety* and *the strip one*. The former emerges as a result of differential movements under the plastic deformation of a rock along the contiguous parallel planes. The property of rocks to be split is conditioned in the case when there is a parallel arrangement of platy (mica, chlorite) and tubular (disthene and others) minerals, as well as the parallel disposition of cleavage planes in these minerals.

Strip cleavage does not depend on the inner structure of a rock and has many features in common with the shear type of jointing. In rocks formed under the metamorphism of sedimentary rocks bedding cleavage, or the schistosity of stratifications, is sometimes distinguished when the cleavage surfaces coincide or are parallel to the stratification in masses of rocks.

In the vast majority of cases *the forms of attitude* of metamorphic rocks are inherited from the original rocks. The forms of attitude of contact and metamorphic rocks, represented by contact aureoles, is exclusive. Depending on a large number of factors the thickness of contact aureoles varies within a wide range. The development of contact and metamorphic rocks often takes place at a considerable distance from the intrusive – along the zones of tectonic deformations or the lamination within enclosing rocks.

The classification of metamorphic rocks is made in accordance with the main types of metamorphism and is based on the genetic principle. The rocks of various types and stages of metamorphism are divided according to their affinity with a particular metamorphic facies and the composition of original rocks.

All the metamorphic rocks are accordingly grouped into *regional-*, *contact-*, and *dynamic-metamorphic* (clastic) varieties. The rocks of regional metamor-

phism belong to the facies of middle pressures (green schistous, epidote-amphibolitic, amphibolitic, and granulitic types) and facies of high pressures (eclogitic). A special place is held by migmatites, or rocks formed in the process of ultrametamorphism and according to physicochemical conditions of formation that are referred to the granulitic facies. Depending on whether the process is reduced to a purely thermal impact, i.e. proceeds without any changes in chemical composition, or is accompanied by its alteration as a result of the influx and evacuation of individual components, contact and metamorphic rocks lend themselves to be differentiated into those that are *properly contact-metamorphic* (contact-thermal) and *the contact-metasomatic ones*. The classification of metamorphic rocks is given in a simplified form in Table 11.

FIGURE 61. The most characteristic structures and textures of metamorphic rocks: Macrotextures: *a* – granoblastic; *b* – lepidogranoblastic; *c* – nematogranoblastic; *d* – porphyroblastic; *e* – cataclastic. Structures: *f* – massive; *g* – gneissic; *h* – schistose; *i* – linear; *j* – plicated

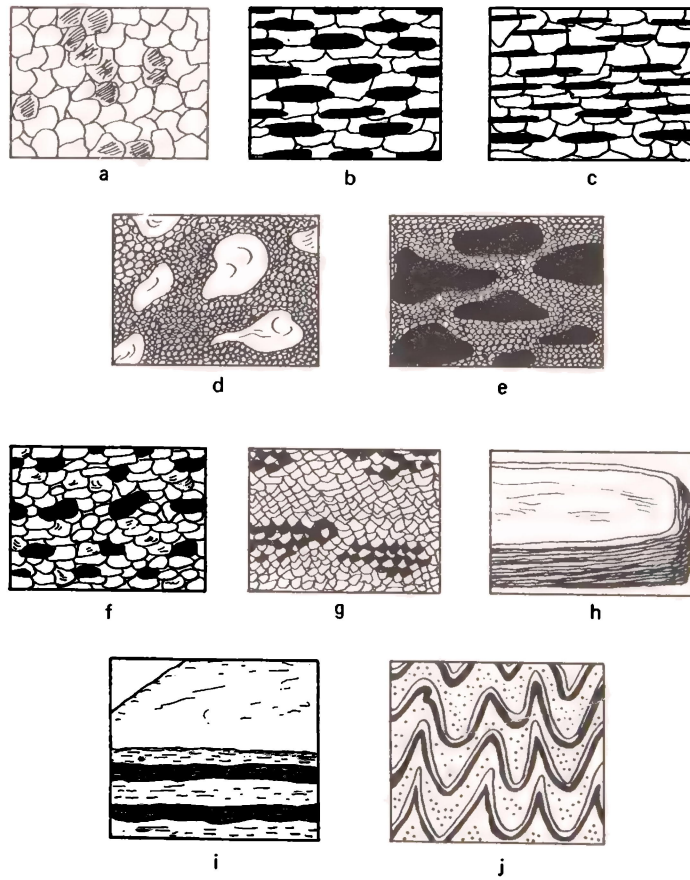


TABLE 11. Classification of Metamorphic Rocks

Type of metamorphism	Metamorphic facies	Metamorphic rocks formed according to parent rocks		
		clay and feldspar	carbonate	basic and medium magmatic greywackes and marls
Regional	green schistous	clay schist phyllite	calcareous schist	chlorite and talc schists, hornblende serpentinite
	epidote-amphibolitic	crystalline schist, quartz	marble	amphibolite
	amphibolitic	gneiss	marble	amphibolite
	granulitic	granulite, migmatite	—	granulite
	eclogitic	—	—	eclogite
Contact-metamorphic proper	hornfelses	hornfels, quartzite	marble	amphibolitic and pyroxene hornfels
Contact-metasomatic	—	greisen	skarn	serpentinite
Dynamic (cataclastic)	—	Tectonic breccia, cataclasit, mylonite		

The rocks of dynamic metamorphism are formed in the zone of tectonic deformations (faults and overthrusts), in which the fracturing and disintegration of rocks take place. According to the degree of fracturing tectonic breccias are distinguished. They consist of sharply angular consolidated fragments. Cataclasites, which differ from breccias in that the size of their fragments is smaller, and mylonites, the rocks that are particularly finely crushed or ground.

Processes of Metamorphism and Their Function in the Formation and Alteration of Mineral Resources

It is not only the transformation of rocks that takes places in the processes of metamorphism. They also greatly influence the attitude and the morphology of mineral bodies, their material composition and the structural and textural characteristics.

In the first place metamorphism results in the alteration of the mineral and chemical composition of mineral resources and their physical properties. For instance, anhydrous oxides are formed instead of hydroxides, thus limonite is replaced by hematite and magnetite, pyrolusite and manganite are replaced by braunite, instead of bauxite we have corundum, and the carbonaceous substance is transferred into graphite. As a rule, metamorphism implies the formation of

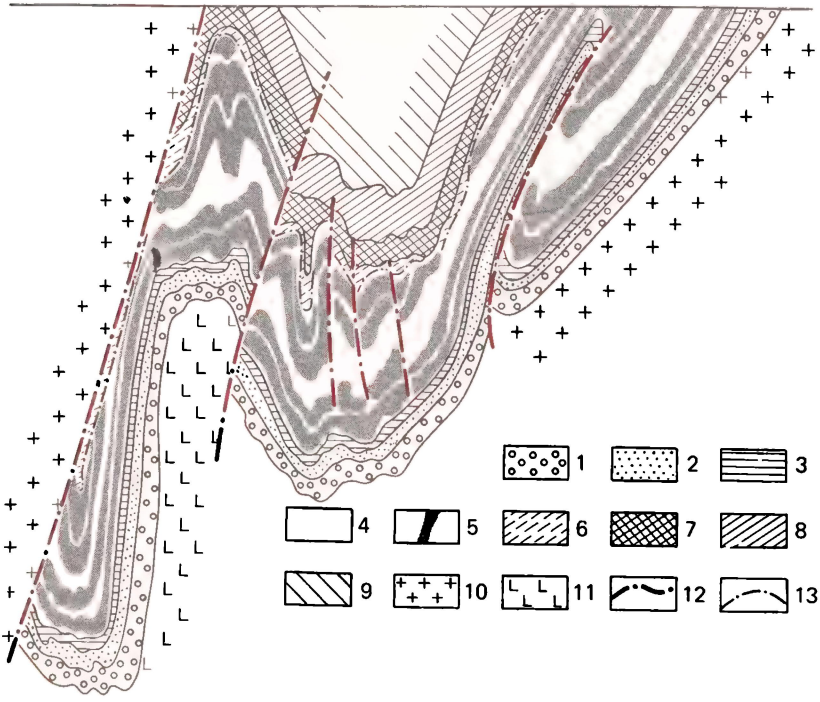
minerals characterized by a smaller specific volume, but with an enhanced degree of compactness.

Alongside the changes in composition, there takes place an alteration of the primary textures and structures of ores. Textures usually become crystalline, and among structures foliated, eutaxitic, plicated, and brecciated types prevail.

All the deposits of mineral resources, the formation of which is connected with the processes of metamorphism, are called *metamorphogenic*. The latter are distinguished as either metamorphosed or metamorphic.

The metamorphosed deposits originate at the expense of those alterations that are pertinent to the previously existing deposits of various genesis. In most cases, it is the exogenic deposits, formed by means of sedimentation, that become subjected to metamorphism. In addition to this, in metamorphosed deposits of iron and manganese at the expense of the formation of simple oxides instead of the hydrated ones, the percentage of useful metals usually increases, and in iron ores the content of such a harmful admixture as phosphorus decreases. In connection with the processes of dynamic metamorphism the originally

FIGURE 62. The morphology and mode of occurrence of metamorphosed deposits. Krivoi-Rog basin (according to Ya. Belevtsev):
1 – arkoses; *2* – phyllites; *3* – talc schists; *4* – schists of iron-ore formation; *5* – ferruginous horizons; *6* – hornblende and sand horizon; *7* – quartz and sericite schists; *8* – carbonaceous and sericite schists; *9* – micaceous and biotite schists; *10* – granites and migmatites; *11* – amphibolites; *12* – tectonic dislocations



sedimentary and laminated bodies of the deposits of iron and manganese ores undergo complex folding, schist-forming process, and, sometimes, jointing and fracture (Fig. 62). In the opinion of some of the scientists, as a result of the influence of dynamic metamorphism upon the chalcopyrite deposits in the Urals, the forms of orebodies were altered. This resulted in the formation of the eutaxitic structures of ores followed by their recrystallization.

Metamorphic deposits represent the altered rocks, which, as a result of the processes of metamorphism, have acquired new useful qualities and have been transformed into deposits of mineral resources. They are mainly represented by non-metallic mineral resources: the deposits of marbles, quartzites, roof schists, andalusite, sillimanite, disthene, graphite, jasper, and others.

In a large number of cases, the ore-bearing deposits include contact-metasomatic rocks, viz. skarns and greisens, which are connected with the deposits of iron, tungsten, molybdenum, tin, lead, zinc, and copper. However, it would be erroneous to refer them to metamorphogenic deposits, since the source of useful components in them is represented by magmatic melts. There is apparently some reason to assert that the contact-metasomatic deposits occupy an intermediate position between the deposits of magmatogenic and metamorphogenic origin.

IV Exogenic Geological Processes

Since the time when the Earth's surface... has been covered with elevated regions forming the continents and the lowerings filled with waters that gave rise to seas, the geological workers... began their job on transformation of this surface.

V. OBRUCHEV

In contrast to endogenic processes the exogenic ones take place in the uppermost layers of the earth's crust at its boundary with the external geospheres of the Earth. Their energy basis is the energy of solar radiation and gravitational forces. Exogenic processes occur under normal values of temperature and pressure in endothermal scheme with the absorption of heat and are directed at the differentiation of the substance entering into the earth's crust. Four groups (stages) of exogenic geological processes are distinguished. They are: weathering, denudation, accumulation, and diagenesis.

Weathering represents the process involving a marked alteration of magmatic, metamorphic and sedimentary rocks and minerals, that have proved to be unstable in conditions of the Earth's surface. The change in physical and chemical state of primary minerals and rocks occurs at the place of their occurrence as a result of the physical, chemical, and biological influence of water, oxygen, carbon dioxide, various mineral and organic acids, living organisms, as well as the direct impact of solar radiation.

Denudation is the combination of removal and transportation processes of weathering products from the place of their formation and direct disintegration of rocks by the agents of denudation (gravitational forces, the waters of continents, seas and oceans, the wind, and glaciers). In displacing the material from the uplands to the lowered parts of the relief, denudation agents lead to the destruction of the Earth's surface and the formation of the levelled out forms of the relief.

Accumulation (sedimentation) covers geological processes, as a result of which loose disintegration products of primary rocks become accumulated in the depressions of the relief, viz. in river valleys, lakes, bogs, seas, and oceans.

Diagenesis (regeneration) is a complex process, which finds its expression in the transformation of the products of exogenic activity (sediments) in sedimentary rocks under the impact of gravitational forces and the change in the physicochemical conditions in the near-surface part of the earth's crust.

All exogenic geological processes are closely interrelated. Owing to weathering there takes place the preparation of material for denudation, while the weathering products that have not undergone displacement themselves become the material for the formation of new rocks. At the same time, the products of accumulation can again be subjected to the processes of weathering and denudation, and so on. The character and intensity of exogenic processes depend on great number of geological, physiogeographical, and other factors. The most important of them are: tectonic movements of the earth's crust, geological structure of the region, relief, climatic conditions, and time.

The main results of exogenic geological processes are expressed in the alteration of the material composition of the upper part of the earth's crust, the differentiation of the substance according to physical and chemical properties, the creation of sedimentary rock masses, and forms of the relief of the Earth's surface. Exogenic processes act favourably upon the formation of the soil and mineral resources. Approximately 60% of all the mineral resources recovered in the world are connected with the products of exogenic activity.

At the same time, the destruction of river banks, the shores of lakes and seas, downfalls and landslides, snow avalanches, washouts and demolitions of slopes, the growth of gullies and the swamping of territories are also the result of the activity of exogenic geological processes, which cause considerable damage to society.

Chapter 12 Weathering

The physical and chemical forms of weathering, which are closely related and usually take place at one and the same time, can be tentatively singled out in its integral and complex process.

Physical Weathering

The processes of physical weathering result in the mechanical disintegration of rocks their grinding and the transformation of original rock in the zone of weathering into rock debris, grass, sand, and clay.

The main factors, which lead to the mechanical disintegration of rocks in the zone of weathering, are changes in temperature caused by the variations of solar activity, the mechanical influence of water during its freezing in rock fissures and pores, the crystallization of salts, the wedge-shaped impact of the developing root system of plants, and the life activity of digging animals. In accordance with the nature of the influencing factor two varieties of physical weathering are distinguished, viz. its temperature and frost types.

The Temperature Weathering. This type of physical weathering occurs as a result of diurnal and seasonal temperature variations, which cause the alternate heating and cooling of rocks, now leading to the expansion and increase in their volume, now to its contraction and decrease. As a result of the regularly recurrent tensile and compressive stresses rocks undergo splitting and fracturing into fragments of different size.

Temperature weathering has a particularly strong destructive impact upon polymineral rocks (granites, syenites, gneisses, and sandstones) due to the various thermal properties of the minerals entering into their composition. Since changes in the volumes of various minerals when heated or cooled are markedly irregular, there emerge in nature the so-called internal stresses, which weaken the force of adhesion between the grains, and thus the rock becomes completely destroyed.

The monomineral rocks (marble, quartzite, and limestone) are also subjected

to temperature weathering since most of the minerals are characterized by the anisotropy of thermal properties in different crystallographical directions. Since the orientation of grains in any rock is highly varied, in the course of temperature weathering there appear local pressures in monomineral aggregates, which finally result in their destruction.

The intensity of temperature weathering is also conditioned by the colour of minerals. Dark minerals are heated to a greater degree and at a greater rate than the light ones, while the process of their cooling is approximately the same. Since the intensity of physical weathering is directly proportional to the amplitude of temperature variations, dark minerals are quickly disintegrated. For instance, gabbro, the composition of which includes 50% of dark minerals, is considerably quickly destroyed than granite, at the same temperature variations.

The intensity of temperature weathering is greatly dependent on the structure and composition of rocks; the equigranular rocks undergo the process of weathering at a slower rate than those that are characterized by a porphyritic texture, while the weathering of coarse-grained varieties takes much less time than the fine-grained or vitreous rocks. Those that have a massive texture are more stable in conditions of rapid changes in temperature than the rocks the structure of which is either foliated or porous. Besides, in rocks that have a foliated structure the heating and cooling along the schistosity occurs two or three times faster than in the direction perpendicular to it.

The mechanical properties of rocks, connected with their structure and composition, also influence the intensity of thermal weathering. Brittle rocks lend themselves to disintegration much more readily than the viscous and fissured ones decompose more easily than those of the compact variety. It is not only the degree of jointing, but also the arrangement of fissures themselves that influence the velocity of weathering. When the fissures are rectilinear and their walls are smooth the disintegration of a rock takes less time and is unimpeded than in the case when a rock contains fissures of irregular form with uneven walls.

The weathering of rocks under the temperature changes begins with their surface, and gradually penetrates into the depth down to the belt of constant temperatures. However, since the outer surfaces of rocks heated by the Sun are poor conductors of heat, they become expanded to a considerably greater extent than their interior parts. This results in that between the surface and the deep-seated parts of a rock there emerge faults that pass along the surface. Along these faults rocks begin to desquamate and exfoliate. The said process involving the exfoliation of the surface parts of rocks is called *desquamation*. The formation of faults along the surface often remains inaccessible to observation and markedly reduces the strength of rocks (Fig. 63).

The destruction of rocks under temperature weathering is most prominent in those climatic regions where there are frequent and marked changes in temperature. On the Earth's surface those regions are the deserts where the diurnal variations in temperature range are as high as 50-60°, while the seasonal ones reach almost 100°. The areas in question also include the slopes of high mountains where, owing to transparency of air, the solar radiation is greater manifested as compared with the neighbouring plains. The intense physical

disintegration of rocks is promoted by fall out of cold rains and hail upon their surface that has been heated by the sun in the conditions of hot and humid climate, as well as by forest and steppe fires.

Frost Weathering. It takes place under the activity of periodically recurrent expansions and contractions, which accompany the process of freezing and thawing of water in the fissures and porous voids of rocks under the temperature changes near the freezing point of water. Since on its freezing and transformation into ice water increases its original volume by approximately 9%, the ice that has thus been formed exerts pressure (of up to 1 000 kg per 1 cm^2) on the fissure walls and breaks even the hardest rocks.

The intensity of frost weathering depends on the presence of water in rocks (water and physical properties of rocks) and the cyclicity of temperature variations near the freezing point of water. The rocks that are most susceptible to frost weathering are the microporous hygroscopic sedimentary rocks (clays, loams, marl, chalk, clay and fine-grained sands) as well as the intensely fissured rocks of any origin. Non-hygroscopic rocks such as gravel and coarse-grained sands, which carry water most readily, remain almost intact as regards the processes of frost weathering.

The temperature cycle greatly influences the depths to which frost weathering penetrates and the size of the rock fragments that are thus formed. If the cycle of freezing and thawing is diurnal (for instance, in the highland regions where the climate is hot), the cold will penetrate to an inconsiderable depth, which results in the formation of thin deposits of small fragments. If, however, negative temperatures prevail over the greater part of the year (in polar regions and in highlands above the snow line), then even within the deep fissures water can reach the freezing point crushing the rocks into large masses.

The phenomena connected with destruction that is brought about by the contraction of water-saturated rocks are known not only to the inhabitants of the Far North, but also to those who live in Moscow. In January 1977 when the temperature of air dropped to $-40\,^{\circ}C$, on some of the highways in the south-western part of the Soviet capital the asphalt covering the roads was broken down into series of gaping fissures due to the overcooling of the loams underlying it. The fissures were up to several millimetres wide.

The property of rocks in a wet state to withhold the frequent freezing and thawing without any marked changes in mechanical strength is called frost *resistance* and is an important feature indicating the quality of building stone materials. It has been established that frost resistance in magmatic rocks is much higher than that of sedimentary rocks.

In the case of frost weathering the rock is destroyed by the forces of ice crystallization. Analogous processes of rock fracture also take place under the influence of the growth of crystals of calcite, halite, sylvine, and other minerals.

Falling out of the aqueous solution, which is contained in the capillary fissures and pores of rocks, the growing crystals exert a pressure upon the walls of fissures that is sufficient for the rock to be crushed.

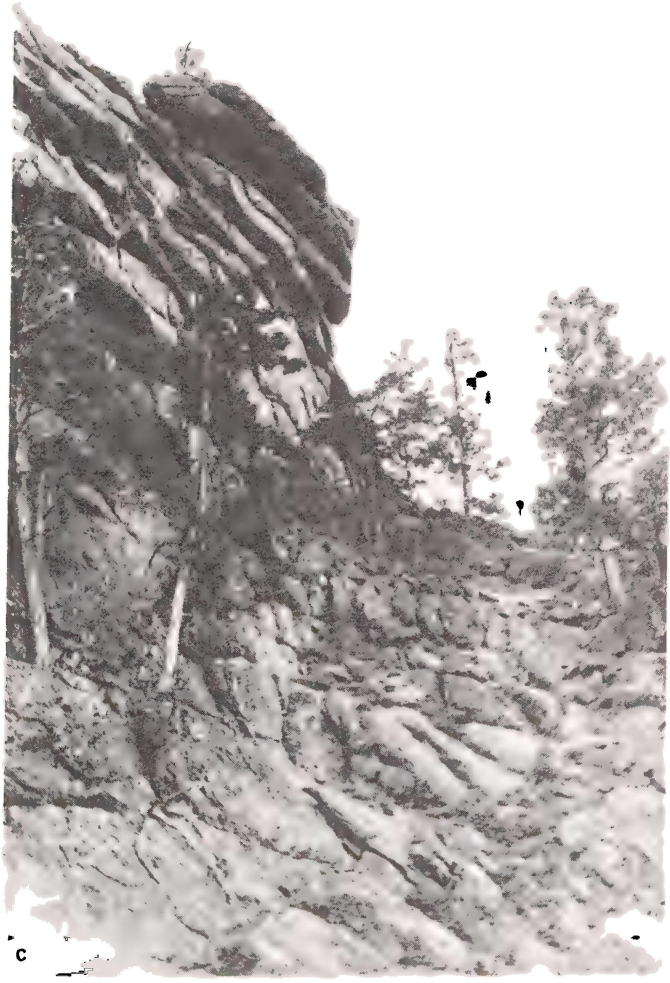
As a result of the growth of crystals the processes involving the disintegration of rocks are most characteristic of zones with an arid climate. In dry and hot

regions the moisture is raised to the surface of a rock along the capillary fissures, after which it evaporates, while the salts contained in it are crystallized as a result of the oversaturation of residual solution.

The role played by the organic life of our planet in mechanical disintegration

FIGURE 63. Results of weathering:
a – Yakut pillars; *b*, c – Lena pillars; *c* – granite massif exposed to physical weathering (Eastern Kazakhstan)

of rocks is of no minor importance. The simplest plants, such as lichens and mosses, which are usually the first to inhabit the newly exposed rocks, destroy the latter most actively within the process of their own life activity. Thus, the traces of destruction can be clearly seen on the surface of the marble column in the Ambrez castle (Austria), which was built over two hundred years ago. Once smooth and polished it is now covered with numerous hollows and holes that have been formed by lichens. In those places where lichens grow most intensely we can see the exfoliation of smallest plates of calcite from the column.



Simplest plants prepare ground for more highly organized plants to inhabit either surfaces or fissures of rocks. Owing to the developing root system wood plants cannot only loosen the soil layer, but are also capable of causing immense damage to compact rocks. It has been established that the pressure developed in the tissue cells of rocks can be as high as 19 MPa. Even the extinct plants can have a deteriorating effect upon rocks. This is connected with the swelling of dead wood after the rain and the expansion of its volume that comes with it. The ancient Egyptians were already well aware of this phenomenon and made use of it in mining operations, when they drove wood wedges into the fissures of rocks and poured water upon them afterwards. A certain amount of mechanical work resulting in the disintegration of rocks is produced by earthworms, ants, thermites, and earth-digging animals.

Chemical Weathering

The Factors of Chemical Weathering. The intensity and trend of chemical weathering are mainly connected with the chemical composition of original rocks, their structure, and also with the climatic conditions and inundation characteristics of the territory. The basic factor of the chemical disintegration of rocks is water, since it intensely acts upon the rocks and is a powerful catalyst, stimulating the activity of oxygen, carbon dioxide, and organic substances dissolved in it.

Magmatic and metamorphic rocks are the ones that are disintegrated in the zone of weathering most prominently. Magmatic rocks undergo chemical decomposition in the said zone at a greater rate. Besides, acid rocks lend themselves to disintegration within a longer period of time than the basic and ultrabasic rocks. Owing to exchange reactions in eroded rocks the content of SiO_2, MnO, Na_2O, K_2O becomes markedly lowered, while that of Al_2O_3, Fe_2O_3 content and water increases. Sedimentary rocks are more stable with respect to the processes of chemical weathering, but with the alteration of chemical properties even they become subjected to disintegration.

The velocity and preservation of chemical weathering products largely depend on the climatic conditions and the relief of the locality. In a humid and hot climate the intensity with which the processes are developed becomes greater, while the thickness of the deposits of end products in the case of a poorly dissected relief reaches 100 m and more. In a cold and arid climate the intensity of chemical decomposition of rocks becomes considerably lower.

No minor role in chemical weathering is attributed to the active life of the organic world. The more organic mass is in the zone of weathering the more intensively the chemical decomposition of rocks takes place. The function of numerous microorganisms is particularly significant. This concerns bacteria, yeast, microscopic fungi and algae, as well as viruses, that according to the means of nutrition are referred to as *autotrophic* type, i. e. those which extract food from inorganic compounds. Most of them are called *lithotrophs*, which, when translated word-for-word from the Greek, means 'those that feed on stones', or simply 'stone-eaters'.

Some of them are capable of absorbing carbon from the carbon dioxide of the air, thus creating their own biomass as the plants do. Others absorb nitrogen, expending a great amount of energy on its fixation. There are those that recover phosphorus from minerals (apatites and phosphorites). And the last group comprises the microorganisms that synthesize their own biomass by absorbing carbon and nitrogen from the atmosphere, and phosphorus and silicon from the corresponding minerals.

The latter have acquired the name of *silicate bacteria*, or *chemolithotrophs*. Chemolithotrophs present an unusual form of the existence of living matter. They easily accommodate themselves in those places where other inhabitants of our planet cannot survive, viz. in hot springs and perennial ice, on ocean floors where the pressure is as high as 100 MPa and more, in super-saline lakes, on the barren hills of mountain tops or in the desert sands scorched by the sun. Thus, for instance, in the water tests recovered from the depth of 2 560 m in the Pacific Ocean, bacteria were discovered that exist in hot jets of the so-called black geysers, the temperature of which is up to 350 °C.

The Processes of Chemical Weathering. All the chemical reactions in the zone of weathering take place according to the exothermal scheme, i. e. with the liberation of heat, and are divided into four groups: oxidation, hydration, dissolution, and hydrolysis. In natural environment these groups of chemical reactions often function at one and the same time.

Oxidation is considered to be the transformation of lower oxides into higher oxides accompanied by the attachment of oxygen. The chemical activity of oxygen becomes markedly greater during its activity in aqueous medium. In addition to this, the property of atmospheric oxygen to be dissolved in cold waters (at 0 °C) is almost twice greater than that in hot waters (at 25-30 °C), which eventually enhances the oxidizing properties of cold natural waters.

The processes of oxidation occur on the Earth's surface, as well as in the zone where atmospheric precipitations permeate into the depth of the earth's crust down to a particular boundary, below which the oxidation processes become totally extinguished. The depth at which this boundary is occurred depends on the material composition and permeability of rocks, the depth of position of underground waters, the dissection of relief, and other factors. In mountainous regions with a markedly dissected relief the redox boundary is situated at the depth of about 1 000 m. In swamped plains it practically coincides with the Earth's surface. It is usually considered that the depth of the oxidation zone on continents is determined by the level of groundwaters.

Those that lend themselves to oxidation most readily are minerals and rocks that contain iron, sulphur, vanadium, manganese, nickel, cobalt, and other chemical elements, which are easily connected with oxygen, as well as organic substances.

The oxidation that is most prominent is that of sulphides. Under the influence of oxygen, dissolved in water, they are easily decomposed by being transformed first into sulphates, and then into hydroxides, oxides, carbonates, and other oxygen compounds. In general, the process of oxidation of sulphides and the transition into readily soluble sulphate compounds can be expressed by the reaction: $RS + 2O_2 \rightarrow RSO_4$, where R is a bivalent metal.

The process involving the oxidation of sulphides can be illustrated by an example of chemical decomposition of pyrite: $4FeS_2 + 11H_2O + 15O_2 \rightarrow$ $\rightarrow 2Fe_2O_3 \cdot 3H_2O + 8H_2SO_4$. In a humid climate the iron that is released in the course of chemical decomposition is transferred into hydroxide of the limonite type, and into hematite in the medium that is poor of water.

Since iron sulphides are the most widespread minerals in the greater part of sulphide deposits, accumulations of iron oxides and hydroxides are formed in the oxidation zone of these deposits. They have received the name of *'iron caps'*.

The thickness of the said deposits varies from 1-2 m to several scores of metres.

The processes pertaining to the oxidation of rocks that have just started are macroscopically easily distinguished by the changes in their colour. As a result of the oxidation of iron rocks become yellow, brown or red; copper ones are found to be bluish-green, carbonate rocks lose their black colour and are turned into those of the light variety, while in the presence of iron acquire a brown colour.

In the process of oxidation the weathered rocks are considerably reduced in their volume as compared with the original ones at the expense of the evacuation from them of easily soluble and volatile newly-formed compounds and the development of porosity at their expense. Thus, the deposits of brown iron ores formed in the process of oxidation of ferruginous rocks and sulphide ores are one and a half times smaller in their volume than the original rocks and ores, which finds its expression in the presence of loose, porous structures.

It is not only hard rocks that are subjected to oxidation, but also the weathering products themselves; particularly those that are situated in the uppermost part of the weathering zone and contain a large amount of extinct organic matter. In the decomposition of the mass of extinct organic matter no minor role is attributed to various microorganisms. When the decomposition of organic remains is complete and takes place at a great rate, and in those cases when in addition to this there is a sufficient amount of atmospheric oxygen, the process involving the transformation of organic substance into the mineral one (the process known as decay) takes place. Instead of the extinct organic tissue we have the formation of oxygen compounds of simple composition (water, carbon dioxide, sulphates, phosphates, and carbonates). When the supply of oxygen is insufficient and the rate at which the decomposition of organic remains is slow, a new and relatively stable complex of organic compounds is formed. It is called mould or humus, and is not only the main element in the fertility of soils, but also the original material for the formation of mineral coals.

The oxidation process is highly significant in recovering, storing and transporting sulphide ores and coals. As has already been mentioned, the more the original material is crushed the smaller the intensity of chemical weathering becomes. Hence, there are often cases of self-ignition as a result of oxidation of recrushed mineral resources in the course of their extraction.

Hydration is connected with the impact of water in its liquid or gaseous state upon minerals and parent rock. In the process of hydration, which often accompanies oxidation, there often takes place the inner restructuring of

a mineral at the expense of the addition of water. For instance, anhydrite, ($CaSO_4$), in the process of hydration is transformed into gypsum ($CaSO_4 \times \times 2H_2O$), and hematite ($Fe_2O_3$) becomes limonite ($Fe_2O_3 \cdot nH_2O$).

Hydration is simultaneous with a marked increase in volume, only if in addition to this there is no evacuation of any readily soluble components. In the above-mentioned process of the hydration of anhydrite the increase in the volume of the gypsum rock becomes approximately as high as 33%. The growth in the volume of hydrated minerals leads to the emergence of inner stresses within a rock, which become responsible for the local dislocations of primary occurrence as a result of the formation of numerous fissures and minor folds.

Dissolution or the transition of a mineral substance into a solution is related to the combined activity of water and carbon dioxide, mineral and organic acids upon the parent rock. All minerals of the earth's crust are soluble, though to a different extent. The intensity of the dissolution of rocks primarily depends on the chemical composition of the rocks themselves and on the chemical activity of the solvent.

Sedimentary rocks are the ones that are most susceptible to decomposition as a result of dissolution. Metamorphic and magmatic rocks are markedly less prominent in this respect. According to the degree of dissolution the priority among the minerals is with chlorides. They can exist in the earth's crust in the form of hard minerals only on condition that they are isolated from water. Sulphates are less soluble, while the dissolution property of carbonates is lower. The dissolution rate of carbonates in contrast to chlorides and sulphates becomes considerably enhanced as the temperature of the solution gets lower.

A very low degree of dissolution is characteristic of sulphides and silicates, though in the presence of carbon dioxide they are too disintegrated with the formation of new carbonate compounds. Thus, in the oxidation zone of copper sulphide ores we have the formation of copper carbonates – malachite and azurite, while at the expense of calcareous silicates (wollastonite, tremolite, and hornblende) there emerges calcite. These reactions of the dissolution of primary minerals with the formation at their expense of carbonates or bicarbonates has received the name of *carbonation.*

A large number of organic acids produced by plants and microorganisms are so strong that they can transfer from rocks into a soluble form various mineral substances that are not decomposed by mineral acids. Humic acids that emerge during the decay of organic remains and which are considered to be very weak organic acids, in the course of continuous activity upon the silicates decompose them with the result that humic salts are formed. There are organic acids that even in the case of poor concentration dissolve quartz, glass, and metallic tin.

Mineral acids (hydrochloric, sulphuric, nitric, and other varieties), which can be present in the zone of weathering, owing to their narrower scope of distribution, as compared with carbon dioxide and organic acids, are known to play a subsidiary role in the general process pertaining to the dissolution of rocks and minerals.

The dissolution of rocks and minerals is most intensely manifested on continents in the condition of humid and hot climate. However, chemical

decomposition of rocks can also be conditioned by the marine environment. This process has received the name of *halmyrolysis.*

The investigation of the factors pertinent to the manifestation and intensity of the natural processes of dissolution and oxidation of minerals and rocks has made it possible to make use of the results that have been received for the elaboration of new geotechnical methods relevant to the development of mineral resources (the method of leaching).

Hydrolysis is the reaction of mineral decomposition under the influence of water, which results in the destruction and rearrangement of their crystalline lattices. It is characteristic of strong bases and weak acids. In addition to this, there takes place the evacuation of properly soluble compounds of strong bases (alkali and alkaline earths) on the one hand, and the adjoining of hydroxyl ions on the other. This leads to the formation of low-soluble disintegration products of primary minerals in new conditions. The hydrolysis phenomenon is connected with the chemical decomposition of those minerals that do not readily lend themselves to dissolution, which primarily concerns silicates and alumosilicates, i. e. the most widespread minerals of the earth's crust.

During weathering of acid magmatic rocks as well as the metamorphic ones the composition of which has very much in common with the rocks of the former type, the first of the major rock-forming minerals to undergo the process of decomposition are micas (biotite, muscovite, and sericite), which are transformed into kaolinite according to the scheme: micas – hydromicas – kaolinite. Somewhat later there takes place the disintegration of hornblende, in the course of which magnesium is evacuated in the form of carbonate, while nontronite and goethite are formed. As a result of the evacuation of potassium, natrium, and calcium feldspars are transformed in accordance with the scheme: feldspars – hydromicas – kaolinite – $Al_2O_3 \cdot nH_2O + SiO_2 \cdot nH_2O$.

Hydromicas, which are extremely unstable minerals in the weathering zone, are considered to be the intermediate products of hydrolysis. Conversely, the chemically stable kaolinite can be accumulated in the zones of moderate climate with the result that fairly thick deposits (kaolin weathering) are formed. However, in tropical zones and when the degree of humidification is high, the process of decomposition can be spread to kaolinite as well. The latter becomes decomposed into aluminium hydroxide (a component of bauxite) and silica. Depending on the relief of the locality and the time within which the process takes place under these circumstances, industrial concentrations of either bauxite (plain relief) or kaolin (dissected relief) are formed.

The hydrolysis of ferromagnesium silicates (amphiboles, pyroxenes, and olivine), as well as basic and ultrabasic magmatic rocks occurs more intensely than that of the acid rocks. The intermediate stage of their decomposition can be characterized by the formation of chlorites and clay minerals of montmorilonite, beidellite, nontronite, and kaolinite. In conditions of humid, but moderately warm climate these intermediate products are fairly stable and often give rise to considerable industrial accumulations of mineral resources. In arid climatic zones the intermediate products of the hydrolysis of ferro-magnesian silicates become unstable and are decomposed with the formation of readily soluble salts, mainly those of calcium and magnesium, which are carried away from the places

of disintegration. The residual products, or almost insoluble oxides and hydroxides of iron and aluminium are accumulated at the place of disintegration (*laterization*).

Weathering Crust

Weathering presupposes the emergence of two groups of its products, viz. *the mobile* ones that are carried away from the place of destruction, and those that are *residual* and remain at the place of the original position of parent rocks. The residual products of weathering represent one of the most important genetic types of continental formations and are called *eluvium*. In most cases the latter consists of poorly sorted out mixtures of rock debris, gruss, sand and clays and represents a loose mass, which, according to its composition, is closely connected with that of the underlying parent rocks. The eluvium, in the formation of which the main function belongs to biochemical agents of weathering, and in the composition of which there is a predominance of organic substances (humus) is called *soil*.

The complex of residual weathering products that are different in their composition and that have emerged as a result of the transformations of magmatic, metamorphic, and sedimentary rocks in continental conditions is referred to as the weathering crust.

The Development Stages and Zonality of the Weathering Crust. The most favourable conditions for the formation of a thick weathering crust are a relatively levelled-out relief of the surface of parent rocks in combination with a hot wet climate and an abundance of organic substances. In young mountain structures distinguished by active tectonic uplifts and active processes of the evacuation of the material that has been destroyed, which the weathering processes cannot 'catch up' with, thin weathering crusts are formed. This is also the case with zones characterized by nival and arid climate.

Four stages in the development of weathering crust are singled out. They are:

the stage when physical weathering and the accumulation of products of coarse mechanical failure predominate;

the stage characterized by the calcitization and removal of easily soluble components in the process of hydrolysis, which include mainly those of sulphur and chlorine, and which are accompanied by the hydration of minerals and the oxidation of sulphuric compounds;

the stage representing the formation of residual clays, e. g. caolins and the evacuation of calcium, potassium, and magnesium from parent rocks;

the stage in which laterites are formed.

As the weathering crust continues to develop into the depth, a number of successive transitory zones from the fresh unaltered bedrocks to the products of a complete chemical decomposition is observed. There are four most typical zones (Fig. 64).

I. The monolithic (cryptofissured) zone, which is correlated with such a condition of parent rock, when it does not yet show any visible traces of fracture, though the bonds between its constituent minerals have already been disrupted.

II. The block zone characterized by the presence of weathering fissures that

promote the disjunction of a rock into separate blocks; the chemical and mineral composition corresponds to that of the parent rock.

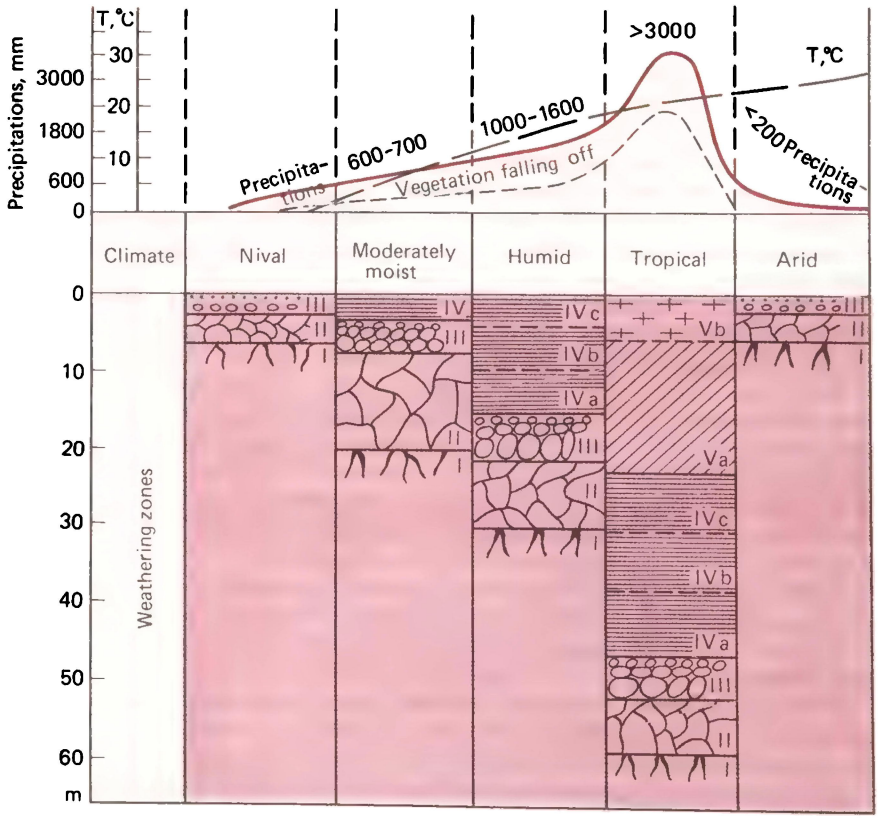
III. The granular, or finely fragmental zone, consisting of fine fragments or individual mineral grains.

IV. The fine-fractured, or clay zone, which is mainly composed of secondary minerals with an admixture of finely fragmented primary minerals.

The boundaries between the zones are uneven, not distinct, and can be displaced with the depth, as the weathering crust continues to develop.

Types of Weathering Crusts. Depending on the climate conditions weathering processes take place at various degrees of intensity in connection with which different types of weathering crust are formed (see Fig. 64). In the regions of polar and nival climate frost weathering is predominant. The fragmental material that is formed is divided into three zones according to the degree of disintegration: the monolithic (cryptofissured) zone, the block zone, and the rock

FIGURE 64. A schematic diagram showing the structure of weathering crusts in different climatic zones



debris zone, which becomes a gruss-sandy zone. The latter is represented by unaltered finely fragmental minerals of primary rocks.

In conditions of moderately warm and moderately wet climate, as a result of a more intense chemical weathering zone (IV) composed of clay material is formed. The latter is predominantly of the hydro-micaceous composition.

In conditions of a hot climate characterized by moderate humidity (a humid climate) at the expense of the chemical transformation of the mineral substance the thickness of the clay zone is developed up to 15-25 m. In addition to this, depending on the composition of parent rocks the zone itselt acquires a zonal structure. Thus, in the weathering crust of ultrabasic magmatic rocks the subzones of montmorillonites (IVa) and nontronites (IVb) are singled out; in the weathering crust of basic rocks the subzones of hydromicas (IVa), montmorillonites (IVb) and kaolinites (IVc) are distinguished; the subzones of hydromicas (IVa) and kaolinites (IVb) are found to be characteristic of the weathering zone of acid and intermediate rocks. The thickness of the zone of physical weathering in the generalized section of the weathering crust is reduced to 10-15 m.

In the conditions of a hot and humid climate of the tropics and subtropics the thickness of weathering crust reaches 40-60 m and more. In the upper part of the crust as a result of the intense hydrolysis of alumosilicates there takes place an accumulation of oxides and hydroxides of aluminium and iron, and partly of silicon (V). This results in that the hardness of dry eluvium resembles a red brick. For this reason these zones of weathering are called *lateritic*. According to the mineral composition and physical and mechanical properties the lateritic weathering zone is subdivided into the subzones of terra rossa (Va) and compact rocks of coarse- and fine-fragmental structure, which look like a shell and that have acquired the name of cuirasses (Vb). The thickness of the zone of laterites can be as high as 15-20 m.

In the regions of arid (dry) climate of deserts and semi-deserts where on account of the lack of water the migration of active substances is markedly limited, the eluvial cover is mainly formed as a result of physical weathering. The weathering products here, as in the zone with a nival climate (the thickness of the weathering crust is considerably smaller) are the accumulations of fragmental material (zones I-III), viz. blocks, rock debris, gruss, and sand. Chemical weathering has a local manifestation in the form of crusts of desert varnish, gypsum crusts, and solonchaks.

The Morphology of the Weathering Crust. According to their formation and form weathering crusts are classified into those that are either areal or linear. The areal weathering crust is developed over vast areas and overlaps the parent rocks at the expense of which it was formed with its cover. Sheet-like in their form and zonal in structure the size of the areal weathering crusts varies between several scores of metres to thousands of metres in cross section with the thickness of tens centimetres to the first score of metres (Fig. 65a).

The linear weathering crusts emerge along the systems of fissures or at the contact with rocks of different composition and have the form of veined-like bodies (Fig. 65b). These bodies are extended along the strike over hundreds of metres, while at the depth they cover several scores of metres, and in fewer cases at the depth of 100-200 m.

According to the time of their formation weathering crusts are divided into recent and ancient ones, or the crusts of fossil variety. The greatest degree of thickness and the differentiation properties of eluvial formations, as well as their vertical zonality, are found in the ancient weathering crusts formed within the stages of the continental development of the earth's crust covering different periods of time. The ancient weathering crusts are connected with such complexes of minerals and mineral resources as bauxites, kaolin, hydroxides of nickel and cobalt, oxides and hydroxides of iron, manganese, opals, magnesites, gypsums, and others. At present the ancient weathering crust is preserved in those parts of the relief, where there is a deposition of younger rocks upon it which protects it from being washed out.

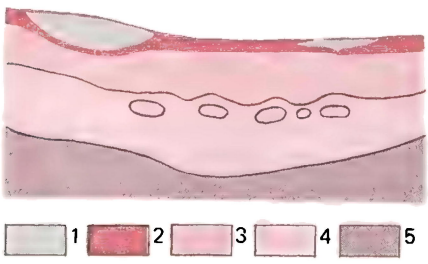
The Role of Weathering Processes

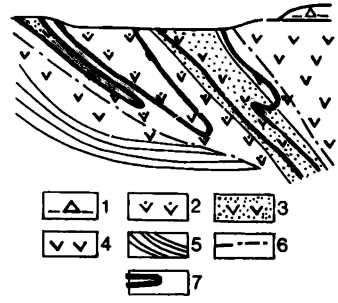
Weathering processes become responsible for the marked transformations of the upper horizons of the earth's crust. In the course of weathering there occurs a fracturing and chemical decomposition of compact and hard magmatic, metamorphic, and sedimentary rocks and their transformation into loose and easily destructible formations.

The enhancement of the degree of jointing and porosity in the process of physical weathering, the alteration of the mineral composition, structure and texture of parent rocks under chemical weathering, lead to the change of the physical and mechanical properties of rocks that are situated within the weathering zone.

The weathered rocks are distinguished by an increased porosity and, as its consequence, by a heightened degree of water absorption. At the same time their strength properties are considerably lower than with new rocks. Therefore, the

FIGURE 65. a. A deposit of the areal weathering crust (section):
1–cover rocks; *2*–ochreous and clay rocks; *3*–non-troniticized serpentinite with an accumulation of nickel minerals; *4*–decomposed serpentinite with an accumulation of minerals of nickel; *5*–weathered serpentinite.
b. A deposit of the linear weathering crust (schematic section of the Cheremsha deposit):
1–deluvium clays; *2*–leached serpentinites; *3*–ochreous and siliceous formations by serpentinite; *4*–weathered serpentinites; *5*–schists; *6*–tectonic dislocations; *7*–ore bodies (contours of)





weathered rocks are weakly stable in the exposure of underground mining operations, slopes of quarries and natural outcrops. They serve as a medium for the origin of talus, downfalls, sills, and landslides. It should also be mentioned that weathered rocks are more easily developed.

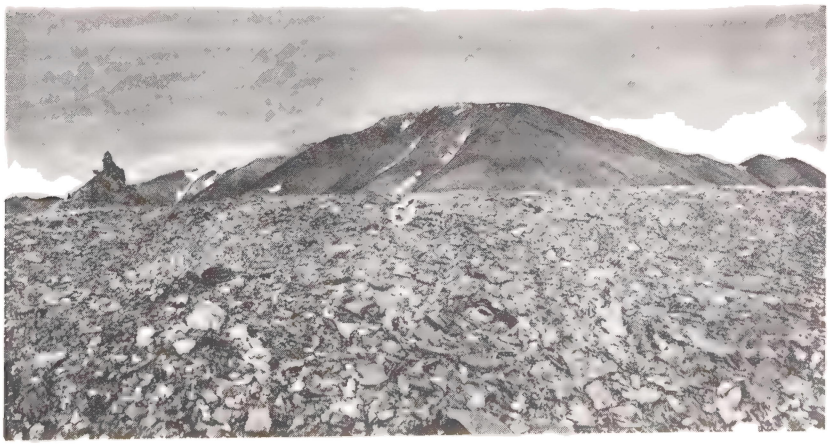
In mining practice, with the importance of physical and mechanical, and primarily strength properties of rocks taken into account, the index, i. e. the degree of weathering, or its coefficient (C_w) is employed. The degree of weathering is taken to be the relationship of the density of the weathered rock to the density of the one that has not undergone weathering. This index characterizes a decrease in the density and strength of the properties of rocks under the influence of physical and chemical weathering.

It is very important to take on the correct assessment of the properties of weathered rocks in projecting quarries, the choice of steepness and the construction of the slopes of road recesses, foundation areas, and flanks of quarries, in evaluating the reserves of standard units of natural stone building materials (marble, granite, quartzite, etc.), in establishing the thickness of the zone where the weathered rocks are removed, the depth of the laying of foundation for the erection of engineering structures, etc.

As a result of weathering, mainly that of the physical variety, special types of landscape are formed. They have the shape of an irregular piling of blocks, which have received the name of '*stone seas*' (Fig. 66).

The weathering processes are connected with the formation and alteration of various deposits of mineral resources. Loose products of physical weathering, e. g. gruss, boulders, gravel, sand and partly clay, represent valuable construction materials, which are used in different branches of industry. In the process involving the formation of eluvium many stable minerals giving rise to the eluvial placer deposits of gold, platinum, cassiterite, ilmenite, diamonds, and others are relieved from the primary rocks. As a result of chemical weathering there emerge the deposits of kaolins, bauxites, nickel, iron and manganese ores. Chemical

FIGURE 66. Stone seas



weathering also causes the transformation of sulphide deposits with low-grade ores of nonferrous metals (for instance, copper) and new deposits and areas characterized by richer supergene ores.

Chapter 13 Denudation Activity of Exogenic Agents

Denudation processes are closely connected with accumulation. It is likewise impossible to imagine accumulation processes without phenomena of denudation, and the rate at which they take place is directly dependent on the intensity of the influx of the disintegration products of primary rocks. The moving forces of these two groups of exogenic processes are exactly the same agents, therefore below we have their general characterization.

Characteristic Features of Denudation and Accumulation Agents

The agents of denudation and accumulation are the variables of the interaction of the Sun's radiation and gravitational forces with the outer envelopes of the Earth: the atmosphere, the hydrosphere, and the biosphere.

The heat of solar rays acts favourably upon the circulation of masses of water on our planet. Evaporating from the surface of oceans, forming clouds, and moving in this form in the atmosphere, waters are brought to the continent and are discharged in the form of rain, snow, hoar frost or hail. Depending on the rainfall and the surface's relief streams, rivers, lakes, and swamps are formed on the continents. A part of atmospheric precipitations that permeates into the depth of the Earth increases the reserves of the underground waters. Most of the continental waters flow back into the ocean, where they become subjected to new processes of evaporation and transportation.

The solar energy is required for the emergence and development of the organic life on Earth. However, in the process of their active life the organisms gradually destroy rocks and are transformed into a new geological agent.

The Wind. The usual distribution of atmospheric pressure on Earth is characterized by the maximum near the pole, a decrease in pressure in subpolar regions, the consequent rise in pressure near N and S 35° L, and the new minimum in the proximity of the equator. As a result of this kind of distribution of pressure the air is raised over the equator, moves at a considerable height towards the pole, descends in the 35° zone and is then shifted near the surface again in the direction to the equator, which results in the formation of winds. Owing to the rotation of the Earth (Coriolis forces) these air flows are deviated from the meridian to the east in the Northern Hemisphere, and toward the west in the Southern Hemisphere.

An additional influence on the migration of air masses and the formation of winds is exerted by distribution of continents and oceans, size and form of land, water masses, the relief, the warm and cold ocean currents, seasonal changes of climatic zones and the seasonal emergence of parts of the territory characterized

by high and low atmospheric pressure. As a result of the incessant movement of the air masses of the atmosphere there take place heat and moisture exchange between continents and oceans, equatorial and arctic zones with the formation of sea currents and waves.

According to the velocity with which air masses move, and which determines the force of their impact on the surrounding objects, the following types of atmospheric conditions are distinguished: calm (up to 0.5 m/s); weak, moderate, fresh and strong breezes (0.5-20 m/s); storm (20-40 m/s); hurricane (more than 40 m/s). Besides, there are air flows that move in circles round the centres of the high and low pressures. They are represented by the so-called *dust-storm* and *waterspouts*. The rate at which the air rotates in a waterspout reaches 30-40 m/s, while the velocity of its movement is equal to 10-20 m/s. As a result of the low pressure of the air within the vortex and a very great velocity the spout sucks into itself, as it were, water, loose deposits and other objects that it meets on its way, and by lifting them up to a great height carries them away over a considerable distance.

The geological activity of air masses in motion is particularly great in the regions of deserts and semi-deserts, vast mountainous areas uncovered with vegetation, on the river banks, the shores of lakes and seas that do not have any vegetation cover either. In the past few decades owing to the intensification of the activity in the interests of national economy, more new regions of the Earth's surface have been involved within the sphere of the active work of moving air masses.

All geological phenomena connected with the activity of wind are called *eolian processes*, while the deposits formed with the help of wind are referred to as *eolian*.

Waters of the Surface Runoff. They are formed from the atmospheric precipitations, and the thawing of snow and glaciers. The total amount of water that flows from continents into the World Ocean is as great as 37 000 km^3 per day.

Depending on the character of drainage the surface runoff is devided into *areal* and *channel*, or *linear* varieties. In the first case the main alimentation sources of surface waters are atmospheric precipitations and the seasonal thawing of snows; on even and gentle slopes these waters are spread in the form of numerous jets, which cover the slope with a thick overlapping network. The virtual power of these jets is essentially the same everywhere. The action of the areal runoff is of short duration and ends almost immediately on the cessation of rain or the thawing of snow. The most favourable conditions for the areal runoff are created within the confines of plain steppe regions of moderate and subtropical zones, in mountainous regions, and on the banks of gullies and river valleys. The process of sheet wash that is accomplished on the slopes by rain and thawing snow waters has been called *deluvial*, and the sediments formed during this process have acquired the term *deluvium*.

In the other case surface waters in the form of linearly elongated jets and streams are collected into particular channels: grooves, troughs, gullies, and river valleys. According to the time and results of their activity channel streams are subdivided into *ephimerial* (temporary) and *permanent* (perennial) ones, or those the activity of which has an *intermittent character*.

Among the temporary streams those of plain territories are distinguished. Owing to them ravines and mountain streams are formed. In most cases temporary streams are brought about at the expense of atmospheric precipitations and the thawing of snow, but sometimes they feed on underground waters as well. The activity of temporary channel streams takes place within relatively narrow and deep-seated localized parts of the earth's crust and depend on the steepness of slopes, the rate at which water flows, the mass of water in the stream and the geological structure of the locality.

Permanent or periodically functioning channels of the surface runoff are rivers; the alimentation of rivers depends on the characteristic features of those places along which they flow. This process is accomplished at the expense of atmospheric precipitations as well as the underground waters, glaciers, lakes, and swamps. Depending on the character of alimentation the regime of river, the amount of water, the level, and the rate of flow change.

In the course of twelve months each river is characterized by the alternation of the periods of *high* (flood or high water) and *low* (low water) *water levels*, caused by an increase or decrease of the amount of water in a river. Thus, in the rivers with the snow alimentation floods begin in spring in connection with the mass thawing of snow, while low water is typical of winter and summer. In the rivers the alimentation of which is glacial floods occur in summer in the period when the thawing of glaciers in the mountains reaches its highest stage. At the time of high and low water the rates at which river waters flow become three-four and more times different from their original values. In addition to this, the velocity of the stream depends on the cross section of the river. Maximum velocity is found in the deeper part of the stream, called the *channel line*. Near the river banks the velocity is considerably lower.

Depending on the character of the relief rivers are classified into lowland and mountain rivers. *Lowland rivers* (rivers of plain) flow in shallow and wide valleys, filled with easily washed-out loose deposits. They are characterized by insignificant stream gradients and a calm flow. *Mountain rivers* flow in deep and markedly narrower valleys, which in most cases are characterized by a stone floor. Their typical features are: a considerable stream gradient, rapid flow, and frequently occurring rapids and waterfalls.

With respect to the characteristic elements of the geological structure river valleys are known to be either non-structural (in the region where the bedding of rocks is horizontal or where they are homogeneous as far as their properties are concerned) and structurally conditioned (in those parts of the territory where rock masses are either dislocated or possess a complex structure). The latter lend themselves to be recognized as either longitudinal, transverse, or diagonal depending on their orientation as regards the line of strike of tectonic structures. Longitudinal valleys extended in the direction of the line of strike are divided into synclinal, anticlinal, monoclinal, and faulted varieties (Fig. 67). This is done in accordance with the type of tectonic structure with which they are correlated.

Irrespective of the type of river, it is customary to single out its three parts. They are: *the upstream* or its upper part, which is connected with the head, *the mid-channel* and *the downstream*, or the lower parts of the river, which terminates in a mouth – the place where the river flows into some reservoir. In the

downstream, rivers (particularly those of the mountain type) have a considerably more gentle stream gradient than in the upper regions. Besides, the greater and more copious the river is the smaller its gradient becomes; the smaller the river is the steeper the slope becomes.

Any river is characterized by its *length, area of the basin,* or *drainage system,* and *water discharge*. The longest river in the world is the Mississippi – Missouri (7330 km). In the Soviet Union it is Lena River (4270 km). Amazon River has the largest basin. Its area is 7000 km^2. In the USSR the largest basin has Ob River, it comprises 2930 km^2. The most powerful river in the world as far as the expense of water is concerned is also Amazon River. Its average-annual expense makes 120000 m^3/s. In the Soviet Union the maximum expense of water has Enisei River (17400 m^3/s).

The general mineralization of river waters changes within a wide range and depends on climatic conditions. In the regions characterized by tropical and subtropical climate the average mineralization of river waters is between 0.5 and 1 g/l, which is considerably lower than the average mineralization of river waters in the regions with arid climate (3-5 g/l).

The waters of most of the rivers in the Soviet Union are insufficiently mineralized (from 0.05 to 0.5 g/l) and according to the composition of the salts dissolved in them are referred to the hydrocarbonaceous type. However, in the droughty regions of the Caspian Sea and Kazakhstan some rivers have a sulphide and chloride composition of waters and their mineralization is approximately 5 g/l. River waters also contain living organisms – algae, mollusks, fish, and other forms. The rivers that are the richest in organic life are those of the tropical zones.

The movement of water in the rivers is *turbulent* (confused, vortical), i. e. the velocity of the movement at each point of the stream is inconsistent as far as the value and direction are concerned. The exponent of turbulence of the movement of river waters finds its expression in vortexes, which bring

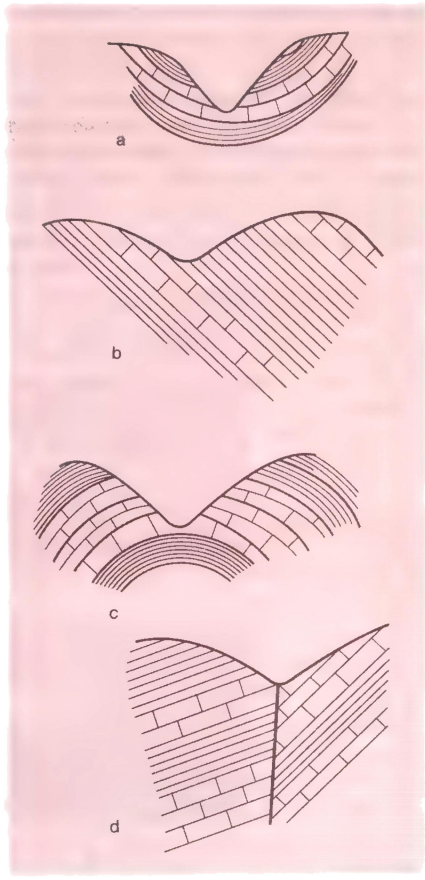


FIGURE 67. Types of river valleys as related to geological structure:
a – synclinal; *b* – anticlinal; *c* – monoclinal; *d* – near fault

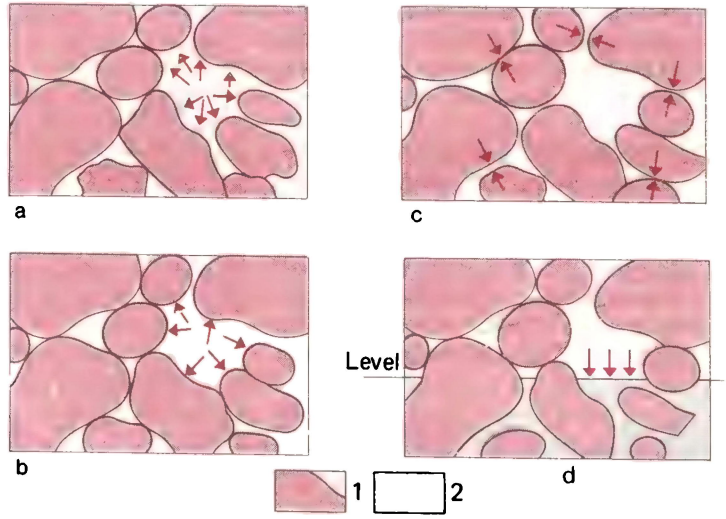
about the agitation of the whole mass of flowing water from bottom to its surface.

Waters of the Subsurface Flow. Underground waters are of various origin. Their main mass emerges in the process of infiltration (seepage) of atmospheric precipitations and thaw waters (*percolating water*). A certain amount of water is formed as a result of *the condensation* of water vapours in the pores and fissures of rocks (*condensation water*). Some water is contained in the form of *inclusions* in sedimentary rocks (*residual water*). Lastly, underground waters also bind their formation to the water that is released during the metamorphism of rocks, as well as to the water of magmatic origin. This is the so-called *juvenile waters*, i.e. the primary endogenic waters. To the depth of 16 km in the earth's crust there are 4000 mln km^3 of water, which makes one-third of the volume of the World Ocean.

The water contained in rocks can exist in different physicochemical conditions (Fig. 68). *The chemically bound water* (crystallization water and water of hydration) enters into the composition of minerals. Besides, crystallization water forms part of the crystalline lattice of minerals in the form of whole molecules (e.g. in gypsum); the water of hydration is added to the colloidal particles and densely envelops them with layers of molecules (for instance, in opal). At a certain temperature the chemically bound water can pass into a free state, and thus acquire the properties of a liquid.

The physically bound water can be either firmly or loosely bound. *The firmly bound* (hygroscopic) *water* is formed from the water vapours that penetrate into the pores of rocks together with air. Adsorbed by the surfaces of hard particles it covers them with a very thin unimolecular film. This water can be released from the rock only in a gaseous state at the temperature of 105-110 °C.

FIGURE 68. Water in rocks (forms of occurrence):
a–hygroscopic water; *b*–pellicular water; *c*–capillary water; *d*–gravity water; *1*–grain rocks; *2*–water



The physically loosely-bound (pellicular) *water* is formed when the quantity of the adsorbed moisture in the pores of rocks becomes greater. In addition to this, a peculiar polymolecular film is created round the particles, which is retained on the surface of rock particles by the forces of molecular attraction.

The water that is contained in an unbound state is found to be susceptible to the impact of gravitational forces and moves relatively free in rocks. *Capillary* and *gravitational waters* are distinguished within this particular type, the former emerge on condition of either partial or complete filling of capillary pores or fissures in rocks with waters, which are kept in them by the forces of surface tension.

Gravitational or free water fills all the fissures, voids and capillaries of rocks and can move freely under the influence of the force of gravity, thus forming concentrations and streams of various velocity and force. When we speak of the geological activity of underground waters what we primarily have in mind is precisely the physically unbound water.

The chemical composition of underground waters is highly varied. The degree of their mineralization changes from practically distilled waters (with the content of dissolved mineral substance less than 1 g/l) to strong brines, in which the content exceeds 50 g/l.

Fifty-seven (out of 93) chemical elements have been discovered in underground waters. The most widespread gases among them are: oxygen, carbon dioxide, hydrogen, ammonia, nitrogen, hydrogen sulphide, and the ions Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}, Na^+, K^+, Ca^{2+} and Mg^{2+}. The presence of these gases and ions in water as well as their combinations determine the basic properties of underground waters, viz. alkalinity, hardness, salinity and their aggressive character with respect to rocks and construction materials.

As concerns the basic chemical composition all underground waters are divided into four groups: hydrocarbonate, sulphate, chloride, and waters of a complex composition, e. g. chloride-hydrocarbonate, sulphate-hydrocarbonate, and others. In accordance with the predominant cation within each group there is a further subdivision of waters into calcium, sodium, magnesium, and mixed varieties. In our everyday life natural waters by their chemical composition are subdivided into alkaline, acid, soft, or hard. The chemical composition of underground waters usually determines their physical properties as well, viz. transparency, colour, density, temperature, taste, odour, and also their usefulness for domestic and technical purposes.

The formation of underground waters and the regime of their activity largely depend on *the hydrophysical properties* of rocks, the most important of which are permeability and moisture capacity.

Permeability, i. e. the property of rocks to pass gravitational water through themselves, is determined by the structural and textural characteristic features of rock, and, in the first place, by porosity and jointing. The degree of permeability is characterized by the coefficient of filtration, which shows the velocity, with which gravitational water seeps through the rock with the underground stream gradient equal to 45°. As a rule, the coefficient of filtration (C_f) is expressed in m/per day.

According to the degree of permeability (C_f) all rocks are divided into groups

or categories: well permeable (pebble-beds and coarse-grained sands), with $C_f >$ > 10; *permeable* (sands and fissured rocks) – $C_f = 1\text{-}10$; *poorly permeable* (marls, sandstones, and loamy sands) – $C_f = 0.01\text{-}1$; *very poorly permeable* (clay sandstones, loamy sands, loams) with C_f equal to 0.001-0.01, and *water-resisting*, or *impermeable rocks* (clays, non-fissured rocks) with $C_f < 0.001$.

Moisture capacity is the property of rocks to enclose and keep a particular amount of water at a given temperature and pressure. According to moisture capacity all rocks are classified into three categories: *moisture-capacitive* (peat, clays, and loams); *poorly moisture-capacitive* (marl, loess, clay sandstones, and sands); and *the non-moisture-capacitive rocks* (magmatic, metamorphic, and compact sedimentary rocks, including those of the fissured variety). For instance, 1 m^3 of clay can absorb and keep from 400 to 700 litres of water, while the figure for quartz sand is not higher than 0.08 l/m^3.

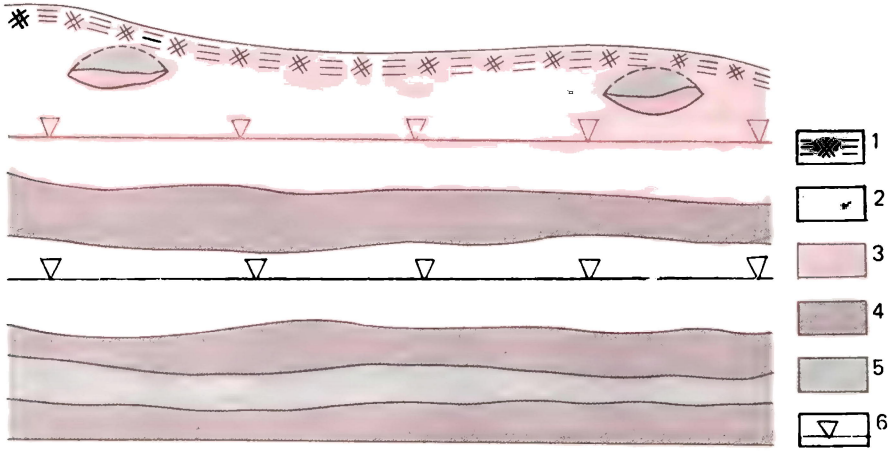
Underground waters, being in a state of incessant motion under the action of gravitational force, move from the region of alimentation into *the area of discharge* or *drainage area* towards river valleys, gullies, sea basins and other depressions of the relief, where they come out onto the surface in the form of springs and sources. Between the regions of alimentation and drainage there is *the flow*, or *transition area*. The rate at which underground waters move is very inconsiderable and varies from 0.1 to 1 m per day, i.e. approximately one hundred thousand times slower than the velocity of the flow in rivers.

According to the conditions of occurrence, alimentation, and movement underground waters are subdivided into soil, vadose, unconfined ground and confined types (Fig. 69).

Soil waters are deposited at the clay surface in the soil layer and represent suspended (not underlain by any aquiclude), hygroscopic, film, and capillary (in

FIGURE 69 A diagram showing the arrangement of different types of underground waters in the earth's crust:

a – soil waters; *b* – vadose waters; *c* – ground waters; *d, e* – confined waters. *1* – soil and vegetative layer; *2* – permeable rocks; *3* – semi-permeable rocks; *4* – aquicludes; *5* – gravity water; *6* – ground water level



the rainy periods) waters. They are formed at the expense of atmospheric precipitations and thawing of snows as a result of infiltration and condensation of moisture from the air. In summer soil waters become markedly heated and are evaporated, which brings about the formation of alkali soils and solonchaks in arid conditions. In winter soil waters undergo freezing again.

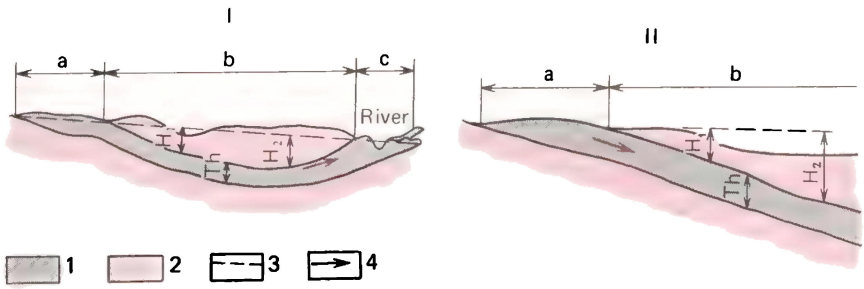
Vadose waters are formed as a result of the accumulation of infiltration waters on the surface of not deeply deposited interlayers or lenses of water-resisting or poorly water-resisting rocks, which are situated among the permeable ones. Film waters, which change into the dropping-liquid variety of vadose waters occupy restricted areas and, as is the case with soil waters, are found to be susceptible to seasonal changes in temperature.

Unconfined ground waters are related to the permeable layer that comes first from the surface and that is occurred in the water-resisting layer, which is the first one from the surface too. The lack of water-resisting roof conditions the alimentation of ground waters within the whole area of their distribution at the expense of precipitations, condensation of water vapours, the waters of rivers, lakes, and seas. Due to the proximity of the Earth's surface and the heterogeneity of enclosing rocks the regime of ground waters is extremely unstable.

Confined waters are distinguished from ground waters in that they have a confining bed which hinders the direct penetration of atmospheric waters from the surface. The source of confined waters is situated at a certain distance from the region of occurrence (sometimes the distance reaches hundreds of kilometres). The underground waters formed in the alimentation area flow down the slope of the aquiclude, and within a very long period of time reach the region of their occurrence.

Confined waters are subdivided into gravity and ground waters. The gravity confined water is found in those places where the water-bearing horizon is markedly drained, and the amount of water with which it is supplied cannot completely saturate the permeable layer. They are usually observed in a dissected relief. The *confined ground* waters (the *artesian*) are formed as a result of a complete saturation of the permeable horizon, which is found at a considerable depth and is not drained by such natural drains as rivers, ravines and other

FIGURE 70. Section of the Artesian basin in trough-like (*I*) and monoclinal (*II*) position of rocks:
a – alimentation area; *b* – pressure area; *c* – discharge area; H_1 and H_2 – pressures; *M* – thickness of artesian stratum. *1* – water-bearing rocks; *2* – impermeable rocks; *3* – piezometric level; *4* – direction of run-off



depressions (Fig. 70). The hydrostatic pressure, which appears in the water-bearing layers, is the greater the more prominent the difference in the heights between the alimentation area and the given part of the water-bearing horizon is, and the less its drainage in the discharge region is found to be.

According to the conditions in which the movement of underground waters takes place, they are classified into *pore*, *stratal*, *fissure*, *karst*, *fissure-vein*, and *mixed* varieties. Pore and stratal waters are typical of permeable rocks. In impermeable magmatic and metamorphic rocks water moves along the systems of fissures. In the zones of tectonic deformations fissure and fissure-vein waters can go down to considerable depths.

Snow and Ice. In certain regions of the world, above the so-called snow line, where the low average annual temperatures are connected with a great amount of falling out hard atmospheric precipitation, there takes place an accumulation of large quantities of snow. The high-altitude position of the snow line is connected with the climatic zonality. In Arctic zones the snow line can be as low as the ocean level (Antarctica, Greenland), while at the equator it rises to the absolute heights of 5-6 km. The snow-line level depends on the local climatic conditions.

As a result of consolidation, temporary thawing and recrystallization, the loose snow that is accumulated above the snow line is gradually transformed first into *granular snow*, or *firn*, and then into compact, hard, transparent and bluish *glacier ice* characterized by a coarse-grained structure. Besides, ice can also be formed during the freezing of surface and underground waters.

The most significant properties of snow and ice, which determine their geological role, consist in that snow leads itself to creeping and consolidation, while ice is readily susceptible to plastic flow that enhances when the values of pressure are high. At the same time, ice behaves in exactly the same way as any other solid body, viz. when definite tensile and compressive stresses are exceeded it tends to expand.

Three types of natural ice are distinguished due to conditions of formation, the character of activity and distribution: ground, drift, and glacier.

Ground (subsurface) *ice* is formed in all climatic zones, where during the winter period rocks freeze from the surface. The depth of freezing is connected with the temperature of the air and the thickness of snow cover. Seasonal and permafrost regions are singled out, in which, within the zone of constant temperatures, water is preserved in the form of ice for a very long period of time.

Drift ice is formed when surface (fluvial, lacustrine, and marine) waters become frozen. Characterized by great mobility, drift ice exerts a considerable impact upon the denudation of continents. Lumps of ice of the subpolar latitudes (icebergs) that are carried away by currents, change the composition of sea water in the process of thawing and lead to specific chemical reactions.

Glacier ice gives rise to large natural accumulations, or glaciers, which are distinguished by a great variety of dimensions and forms. In the present epoch they cover more than 10% of land on our planet.

Owing to the plasticity of ice and forces of gravity, all glaciers move from the region where ice is accumulated (alimentation area) into the region of discharge, wherein they undergo gradual thawing. The rate at which glaciers move depends on the size of glaciers, the amount of atmospheric precipitations in the

alimentation area, the relief of the glacial bed, the time with which the ice thaws, and its temperature. The middle part of the glacier usually moves at a greater rate than the benthonic and lateral parts. In general, however, the rate at which glaciers move is inconsiderable, and is measured in scores and in the first hundreds of metres a year. Only some of the largest glaciers in Greenland, where the thickness of ice is measured in kilometres, their velocity ranges from 5 to 40 m per day. In the Himalayas their annual rate of movement hardly reaches 700-1 300 m while for most of the glaciers in the Alps, Middle Asia, and the Caucasus, the speed varies from 0.1-0.4 m per day.

According to the form of alimentation areas and the character pertinent to their movement, glaciers are divided into two main types, viz. those that are continental, and the Alpine ones.

Sheet glaciers, or *ice caps* cover 98.5% of the contemporary glaciation area and are spread practically throughout the Antarctica, Greenland, and the vast regions of Iceland, Spitsbergen, Novaya Zemlya, Severnaya Zemlya. The distinctive features of sheet glaciers are their enormous dimensions and the absence of any clear-cut boundaries between the alimentation and discharge areas.

Alpine glaciers are characterized by a relatively small size, a clearly expressed boundary between the areas of alimentation and discharge, and a close link between the forms and the direction of movement from the relief of the surfaces that underlie them.

Lakes. The now existing lakes on the Earth's surface cover approximately 1.8% of the land and are very irregularly distributed within the confines of plain territories as well as at various heights in the mountains. According to their origin the lake depressions are subdivided into endogenic, exogenic, and mixed varieties.

Endogenic lakes are formed when water fills the depressions of tectonic origin, the craters of extinct volcanoes, as well as basins that emerge as a result of the swamping of valleys by lava streams; these include *the tectonic lakes*, e. g. lakes Baikal, Teletskoye (USSR),Loch Ness (Great Britain), large lakes in East Africa (Victoria, Tanganyika, Kivu); and *the volcanic lakes* of Kamchatka, the Kuril Islands, the Lake Sevan that was swamped by the lava streams.

Exogenic lakes are subdivided into *glacial, river, plunge-basin* (the activity of underground waters), and *the dammed varieties.*

Lakes of the mixed type were formed owing to the synchronous influence of endogenic and exogenic processes. For instance, lakes Ladoga and Onega are confined to the zone of tectonic deformation of the fault type, though the shape that they now have may well be attributed to glacial processes. Some of the lakes are the relicts (relict lakes) of the former sea basins (the Caspian and the Aral lakes).

According to *the hydrological regime*, lakes are classified into those that are of drainage and closed drainage types. *The drainage lakes* are mainly spread in the regions where the climate is humid. *The closed drainage lakes* do not have any drainage, and the whole supply of water in them is taken up by evaporation.

In accordance with the chemical composition and the degree of mineralization of waters, which depend on the chemical composition of the incoming waters, the

composition of rocks entering into the structure of the lacustrine basin, the relationship of evaporation or the expense of water to its supply, lakes are known to be of either *fresh-water* or *salt* types. According to the composition of the dissolved substances, lakes are distinguished as either *carbonate mineral, soda, sulphate mineral,* or *chloride mineral varieties.* In some of the crater (volcanic) lakes alongside the chloride, sulphate, and other compounds there is a vast amount of silicon, iron, and aluminium oxides, and sulphur.

Swamps. The swamps are parts of the Earth's surface that are characterized by an excessive humidification of the upper horizons of rocks and the development of moisture-loving palustrine vegetation. At present, the total area covered by swamps on Earth is estimated to be 2 mln km^2, of which 70% are accounted for by the territory of the USSR.

The emergence of swamps has its roots in various elements of the relief, in those parts where underground waters stand high and where they come out onto the surface. Swamps are very often formed on the place of lakes, on floodplains and in the deltas of large rivers, on littoral lowlands, and within the vast spaces where the perennially frozen rocks are developed. According to their origin swamps are divided into *the inland* (eutrophic, oligotrophic, and mesotrophic) swamps and *the marine* ones. A particular type of swamps is developed on floodplains and in the deltas of large rivers. This finds its expression in flooded river banks (*plavni*)* and spring fens.

Seas and Oceans. The geological activity of seas and oceans depends on the relief of the floor, the mobility of the earth's crust within the confines of sea basins and the surrounding land, the chemical composition, temperature and gas regime of sea waters, the movement of the latter, etc.

In the relief of the World Ocean bed several large geomorphological zones are singled out, each of which is characterized by its own physicochemical conditions in which the processes of denudation and accumulation take place. They are: the littoral zone, submarine continental margin (shelf), continental slope, and the World Ocean bed (see Fig. 6).

The littoral zone is subjected to either permanent or temporary impact of sea waves. *The shelf* edges all the continents and islands of inland origin. In the proximity of young mountain structures the width of the shelf hardly reaches several kilometres. At the same time, at the gently sloping shores it exceeds 1 000 km. The depth of the floor within the confines of the shelf is not usually greater than 200 m, in rare cases going down to 500 and even 2 000 m (the Sea of Okhotsk). *The continental slope* is characterized by an inclined position of the floor surface at the angles between 3 and 6-7°, in places up to 10-15°, down to the depths of 2 000-2 500, and in fewer cases reaching 3 000 m and more. The foot of the continental slope represents a gently sloping and at times slightly undulated plain, which passes onto the levelled-out spaces of the oceanic bed. *The World Ocean bed* covers about 50% of the area of the bed and is situated at the depths of 3 500-6 000 m. The surface of the ocean bed has a highly complicated dissected relief, which resembles that of the surface of continents. This kind of surface

* Plavni – of downstream valleys of some Russian rivers covered with reed and trees.

structure of the World Ocean bed gives rise to contrasting conditions in which geological processes occur, since the density, salinity, pressure and gas regime of oceanic waters undergo substantial changes with depth.

The waters of seas and oceans represent *natural solutions*, the composition of which includes practically all the chemical elements that have so far been discovered. However, in quantitative terms, the composition of sea waters is remarkable for a marked predominance of only four chemical elements, viz. oxygen, hydrogen, chlorine, and natrium, which account for 99.5% of the composition as a whole. The other elements dissolved in sea water comprise insignificant quantities ranging from tenths to billionths of one percent by weight.

A characteristic feature of the chemical composition of the saline mass of sea water is a marked excess of sodium and magnesium chlorides (NaCl–77.8%, $MgCl_2$–10.9%) and a low content of carbonates, compounds of nitrogen, phosphorus, silicon, and organic substances, which in the marine medium are accumulated by its inhabitants and serve as the material for their shells and skeletons.

The waters of the World Ocean contain various dissolved gases, the quantity of which varies from 5 cm^3/l at the equator to 8 cm^3/l in high latitudes. The content of gases depends on temperature conditions and pressure; it increases when the temperature is lowered and the pressure becomes higher.

The main *gaseous components* of sea waters are oxygen, nitrogen, carbon dioxide, and hydrogen sulphide. They determine the living conditions of most of the marine organisms, influence the directivity and velocity of endogenic processes, and the character of sedimentation. Oxygen and carbon dioxide are supplied from the atmosphere. Their considerable influx is connected with the activity of organisms, while the delivery of carbon dioxide may be correlated with the submarine eruptions of volcanoes. In the waters of the World Ocean hydrogen sulphide can be found in extremely small concentrations. However, in some of the continental seas in the deep layers of water it is discovered in large amounts as a product of activity of anaerobic bacteria, the decay of the remains of organisms and the penetration of juvenile hydrogen sulphide into sea water, which serves as a powerful reducing agent. Thus, hydrogen sulphide gives rise to specific conditions in which geological processes take place.

The temperature of oceanic and sea waters is determined by climatic conditions. In the upper layers of the ocean water the average annual temperature diminishes rather gradually from the equator to the poles, from + 25 to 0 and even 2-3 °C below zero. At the same time, it regularly changes with depth. The surface layer of water is found to be most subjected to temperature changes of the atmosphere. In the upper layers down to the depth of 10-20 m the temperature of water changes within the period of 24 hours, while down to the depth of 200-300 m variations in temperature depend on the seasonal climatic cycles. At considerably greater depths the temperature of water is not so much subjected to changes and varies between + 2-3 to − 1.9 °C in the polar parts of the oceans.

In marine conditions *pressure* is directly related to the depth of the basin: the increase of depth per 10 m is accompanied by the growth of pressure by 1 atm

(10^5 Pa). Under the influence of water pressure and with the increase in depth, a large number of chemical reactions begin to increase the rate at which they take place.

The organic world is an inherent and characteristic part of sea and ocean waters. It is extremely rich. Thus, in the Mediterranean Sea there are more than 7 000 species of organisms; the figure for the Black Sea is 1 200.

According to the conditions of their habitation and movement marine organisms fall into benthonic, planktonic, and nektonic types. *Benthonic* forms are inhabited on the bottom of sea basins. Depending on the way of life benthonic forms can be either sessile or mobile. They reach maximum development in the shelf zone. The plant organisms that refer to benthos include various algae. The animal organisms comprise: sponges, corals, and the crustaceous.

The planktonic organisms do not possess the property to move actively and are passively displaced in water by waves and currents. Zoo- and phytoplankton organisms are distinguished. The former (animal organisms) include foraminifers with calcareous tests and radiolarians with tests consisting of silica. Phytoplanktons (plant organisms) comprise various algae also including diatoms enclosed in a siliceous shell. An enormous concentration of planktons is found in the upper layers of the World Ocean down to the depth of 200 m.

The nektonic forms are animal organisms, which can actively move in water surroundings. They include sea mammals, fishes, sea-urchins, starfish, and some of the mollusks.

The shelf zone accounts for approximately 80% of the whole biomass of the World Ocean. The development of biological life on the continental slope and the ocean bed is restricted by an enhanced density of water, inconsiderable amount of oxygen contained in water, and the absence of the light of the Sun.

The geological function of organisms, inhabiting the World Ocean can hardly be overestimated. There exists a constant interaction between organisms and sea water. The organisms assimilate some of the components, emanate and transport the others. After dying off of organisms masses of biogenic sediments are formed.

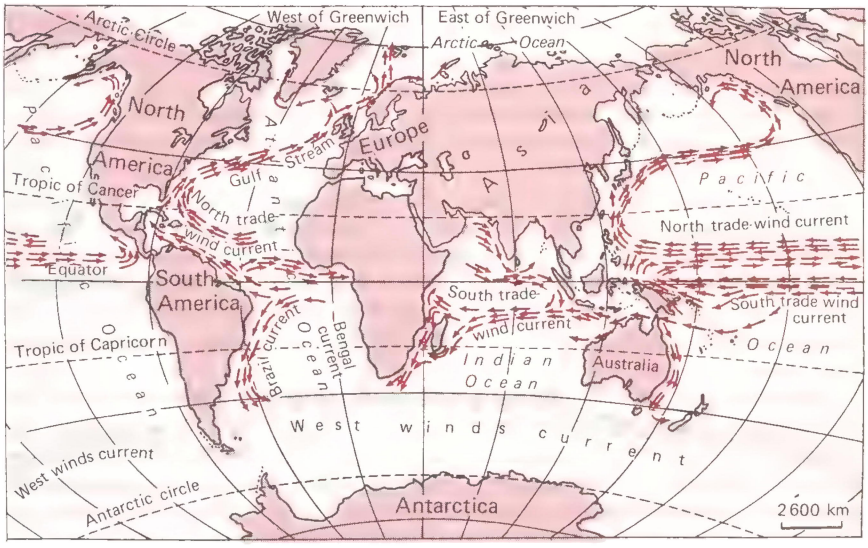
The waters of the World Ocean are in a state of motion, constant displacement and circulation, which is accounted for by various factors. It has been found relevant to distinguish wind-driven waves, caused by the action of wind upon the water surface, tidal movements, and constant sea currents.

Wind-driven waves represent oscillatory motions of water particles in the upper layer of the hydrosphere, which produce enclosed circular orbits in the vertical plane and, at the same time, perform forward motion in the direction where the wind is active.

At the shores and in the shallow water areas the wind-driven waves of the sea have quite a different character. What we have here is a retardation in the movement of the particles as a result of the friction on the sea floor. The oscillatory wave motions become transformed into those that are forward. The wave overturns and forcefully breaks against the shore or floods the low coast. This kind of movement is called *surf*.

The tidal waves emerge periodically (every 6 hours and 12 minutes). The transportation of water in open sea during high and ebb tides presupposes the participation of the whole mass of water. In addition to this, at considerable depths water particles describe enclosed elliptical orbits which results in the formation of sea currents.

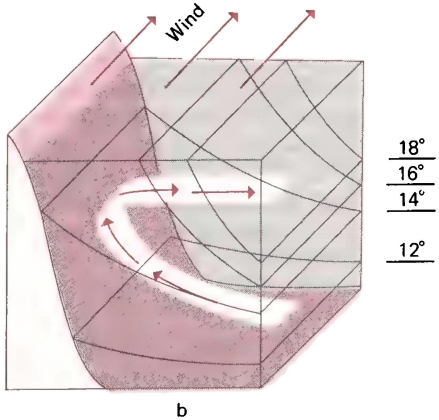
The velocity of tidal currents changes as the depth increases and makes 10 m/s



a

FIGURE 71. The currents of the World Ocean:

a – warm currents and cold currents; *b* – upwelling



b

on average. The level of water at the time of high tide varies from 0.6 m in the central parts of the ocean to 6-8 m at the shores of marginal seas. Particularly high tidal waves are registered in the narrow bays, straits and mouths of rivers. Thus, in Penzhina Bay (the Sea of Okhotsk) the height of flow tide reaches 12 m, while in the funnel-like Bay of Fundy (Canada) it is 18 m.

As a result of earthquakes or submarine eruptions of volcanoes there emerge gigantic waves in oceans. They are called *tsunami*. The rate of their movement reaches 800 km per hour; their length can be as great as 200 km, and they can be as high as 20-30 m in shallow water areas.

If wave movements are predominantly manifested near the water surface, *sea currents* cover vast masses of water of both the surface and the deep layers (Fig. 71*a*). Brought about as a result of the difference in temperatures, salinity and density of sea waters, the activity of constantly blowing winds as well as owing to Coriolis forces, sea currents, in the same way as rivers on the continents, move in the form of wide bands at various degrees of speed and cover enormous distances.

Extremely powerful currents appear in the proximity of the equator under the influence of trade winds. These are the Kuroshio Current in the Pacific Ocean and the Gulf Stream in the Atlantic Ocean. The length of each of them reaches 5 000 km with the width of flow of up to 100-150 km and the rate of water movement measuring up to 144 km per day. The discharge of Gulf Stream, until it reaches the Florida Current, is 3 000 times greater than that of the Volga River at its mouth.

A highly important geological role in the ocean is attributed to the so-called *upwelling*, or the motion (rise) of waters from the depths towards the upper layers of the ocean (Fig. 71*b*). Upwelling is particularly active in the coastal oceanic and sea zones, where under the activity of directed winds and currents there takes place a rise of water from the depths of 100-300 m. A powerful and stable upwelling is mainly connected with trade winds and eastern marginal currents in the Atlantic, the Pacific, and other oceans. The total area of the constant upwelling manifestations is estimated to be approximately 1 mln km^2, with the average vertical velocity of the water uplift equal to 1 m per day.

Gravitational Forces. The activity of gravitational forces manifests itself in those cases when gravity exceeds the values of resistance, conditioned by the strength and coherence of the materials, the friction between them and the contiguous materials, as well as by various external supports.

The main factors conditioning the geological activity of gravitational forces are the composition and structural features of rocks, the content of moisture in them, the relief of the surface, climatic conditions, and the presence of vegetation. Besides these main factors, additional ones are also distinguished. They are those that either enhance the gravitational force or diminish the force of resistance.

Denudation Activity of Exogenic Agents

The destructive work on the Earth's surface produced by air or water masses of the channel flow has received the name of *erosion* and is estimated in quantative terms by the formula $A = mV/2$, where m is the mass of air or water

and V the flow velocity of either the air or water current.

The Eolian Erosion. The destructive work of the moving air masses depends on the velocity of the wind when air streams are in direct contact with loose or poorly consolidated rocks, as well as when hard particles transported by air streams act upon the surface of rocks. The first type of eolian erosion is called *deflation.* The second type is known as *corrasion.*

In the process of deflation the wind takes up the loose weathering products or tears away little particles of a poorly consolidated rock and transports them in its own direction. Deflation has a selective character. It is not infrequent that in steep precipices composed of layered masses with different physical and mechanical stability of rocks, protrusions and benches, corresponding to the layers of stable rocks, alternate with deflation recesses in soft or poorly consolidated rocks.

The work of wind becomes particularly noticeable in the process involving the transportation of fragmental material. The remoteness of transportation, the amount and manner in which the material is transported depend on the size of the particles that undergo transportation and the velocity of the wind.

The amount of material that is transported by the wind occasionally reaches hundreds of thousands and even millions of tonnes. According to the estimates of the specialists, the wind has carried away the layer of sediments measuring 2.5 m in thickness from the area of the Nile within the past 2 500 years. On Canary Islands there has been a fall-out of dust brought from the Sahara desert, the mass of which was established to be 10 mln tonnes.

The mechanically suspended particles transported by the wind are known to produce a destructive work by constantly bombarding the surfaces of obstacles with which air currents are met on their way. As a result of this kind of bombardment (corrasion) and depending on their physical and mechanical characteristics rocks are smoothed, abrased, grinded down, and bored out, i.e. undergo various types of destruction. In rocks peculiar forms of niches, furrows, and scratches appear; microscopic fissures that have so far been inaccessible to observation become markedly wider; caves of inconsiderable depth emerge, etc. In the corrasion of coarse-fragmental and porous rocks that are heterogeneous in their composition honeycomb deflation forms come into existence.

Since in the air stream mechanical admixtures are differentiated according to density and mass, the foundations of rock massifs are found to be most susceptible to intense corrasion. Depending on the position of rocks and their physical and mechanical properties there emerge deflation forms of the mushroom type and pillars in the case of gentle slip of rocks, as well as in the form of columns, spines, and obelisks when the dip is of steeply pitching variety. Thus, as a result of corrasion and deflation particular eolian forms of the relief are formed (Fig. 72).

The destructive work of surface runoff waters consists in *sheet erosion* of weathering products from the slopes of the elevated parts of the relief (deluvial processes) and the *channel washout* of rocks by the moving water streams (erosion processes).

In the case of *sheet erosion* temporary water streams cover a part of the loose and mainly fine material and transport it to the foot of the slope. Owing to this

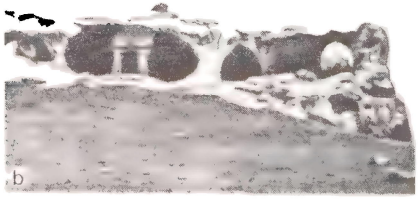
process vast areas of slopes are smoothed out and flattened with the overall levelling of the surface of continents and a diminishing of its vertical dissection.

The intensity of sheet erosion is determined by the volume of the flowing down water, the steepness of the slope and the lack of any vegetative cover on the way of its movement.

The deluvial removal can often prove to be very threatening for agriculture and mining. From the slopes of the uplands fertile soils are washed down; the edges of quarries composed of loose rocks undergo over-moistening, which results not only in the washout of the upper and more mobile layer, but also in the creation of appropriate conditions for the aqueous and gravitational processes (landslides and mud-streams).

Channel (linear) washout brought about by water streams is developed in accordance with the physical laws of hydrodynamics and finds its expression in the process involving the interaction between the forces of flowing water, which washes the bed of the stream, and the resistance to the washout of the rocks that constitute its bed. The activity of flowing water is determined by the energy of the stream (the living force), and depends on the velocity of the flow, which is directly proportional to the gradient of the bed, as well as to the mass of water in the stream.

The erosive activity of a water stream



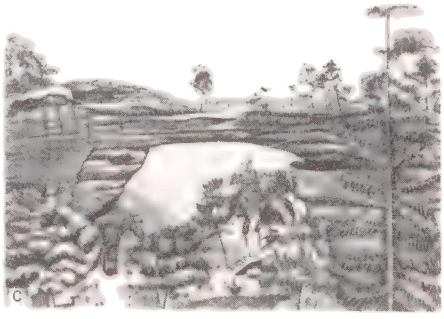


FIGURE 72. Eolian forms of the relief:
a – rock pillar (Eastern Siberia) (photo by V. Rzhevsky); *b* – rock arch in Cretaceous sandstones (according to V. Obruchev); *c* – eolian recesses in sandstones (according to V. Obruchev)

represents a complex process, which includes the removal of fragmental material by water, the mechanical disintegration of rocks in the stream bed and the dissolution of soluble rocks by water in the course of its movement.

The mechanical disintegration of rocks by water streams is carried out under a given rate of water movement in the stream and the supernormal pressures upon rocks exerted by water pressure. Depending on their composition and structural and textural features, various types of rocks become involved in the process of washing out at different velocities of water moving in the stream. Thus, clay rocks lend themselves to disintegration when the velocity of stream is 0.15 m/s, the figure for sandy rocks is 0.3-0.4 m/s; that of poorly consolidated varieties is between 1.0 and 1.2 m/s; mica schists become subjected to destruction when the rate at which the stream moves is 1.5-1.8 m/s. Gabbro and syenites undergo destruction when the said kind of velocity changes between 3.0-3.2 m/s. The ultimate values of strength properties function as a boundary of the destruction of rocks under the pressure of water.

The fragmental material that is transported in a suspended and dragged state is called *the hard runoff* of the water stream. The fragmental material is transported by channel streams (particularly rivers) in very large quantities. For instance, every year the Don River carries out into the sea 14 mln t of mineral particles; the hard runoff of the Volga River comprises 40-50 mln t, while the runoffs of Amu Darya and Amazon Rivers are 217 and 1 000 million t, respectively.

Owing to the presence of a hard runoff in a water stream the washing away of the destructed material takes place simultaneously with *water corrasion*, which is expressed in the mechanical abrasion and scratching of the stream bed by rock fragments dragged along by water.

The chemical transportation of the mineral substance dissolved in water is no less significant than the hard runoff. For instance, the Don River annually evacuates into the sea about 6 mln t of chemically dissolved substances, with the Volga River the amount reaches 46.5 mln t, and 17.7 mln t are accounted for by the Amu Darya. Water streams are also found to be responsible for the transportation of organic matter. Thus, the rivers of the Urals evacuate 11.2 mln t of organic material every year, while the figure for the Volga is 16.2 mln t within the same period of time.

In different stages of the development of the water stream its erosive activity changes not only in value, but also in its directivity. Two types of erosion are distinguished. They are the river-bed and lateral varieties. *The river-bed erosion* is characterized by the processes of washout and the channeling of the stream bed floor (the entrenchment of the stream into the rocks of the floor) by the forces of moving water. *The lateral erosion* finds its expression in the destruction of the foundations of the walls of erosional furrow by water streams, as a result of which there occurs the widening of the channel bed.

In the initial stage of its development the erosive activity of the water stream begins with the river-bed erosion. The level of the channeling of the stream bed, below which the water stream ceases its activity, is called *the base level of erosion.* For most of the water streams on the continents the base level of erosion is the level of the World Ocean, which is called *the absolute base level of eroesion.*

Besides, there exist local base levels of erosion, representing the levels of drainage reservoirs. For instance, for streams and minor rivers this can be the level of rivers and lakes, into which they flow. Temporary or mobile base levels of erosion are also distinguished. They have the form of various obstacles for water streams (dam or the outcrops of other rocks).

To a considerable extent the rate of entrenchment depends on the composition of rocks constituting the stream bed. Along the friable rocks (pebble-beds, sands, and silts) even very small channels rapidly deepen their bed. More difficult water streams entrench themselves into clay rocks, homogeneous limestones, loose sandstones, and poorly consolidated volcanic tuffs. The process of washing-out is very slow with massive crystalline rocks (granites, gneisses, and gabbro), the outcrops of which are the mobile base levels of erosion and in a large number of cases hinder the further development of river-bed erosion upwards along the channel for a long time. In these parts of the water stream there emerge waterfalls, and bars (rapids).

In due time the stream works out its own bed, which has the form of a smooth concave curve that gradually goes down to the base level of erosion and is steeper in the upper regions (Fig. 73). This kind of longitudinal profile of the water stream is called *the profile of equilibrium* or *the ultimate erosional curve.* Under homogeneous conditions the profile of equilibrium finds its expression in the lower parts of the stream. This is where the entrenchment ceases and is gradually replaced by accumulation. In later stages fragments of the profile of equilibrium appear still higher along the flow, and in due course reach its higher regions (the phenomena of retrogressive, or backward erosion). Thus the development of river-bed erosion process develops from the mouth of the stream to its upper parts.

When the longitudinal profile approaches the position of ultimate erosional curve the river-bed erosion continues to retard, while the released energy of the stream is expended on the widening of the channel, i. e. the stream enters the stage of lateral erosion. In accordance with Coriolis acccleration in the Earth's Northern Hemisphere in the large channels it is the right shore that is undermined more intensely, while in the Southern Hemisphere the same can be said of the left shore. The stream flow reflected from the undermining bank is deviated in the opposite direction. On the thus emerged bend of the race systems of transverse circulations of water come into existence. They are particularly clear manifested at the time of floods.

The formation of a channel bend at one place inevitably results in the emergence of a whole series of bends conjugated with it down the flow, since the race will consecutively be reflected now from one, now from the other bank (Fig. 74). The thus emerged channel bend gradually becomes greater in size until its neck (I) is so narrow, that at the time of flood waters will be able to break it through and straighten the channel again (II). Thus, owing to lateral erosion the channel bed does not merely become wider, but also acquires a loop-like form, i. e. the river is said *to meander* (the term being derived from the name of the Meander River in Asia Minor). The further widening of the channel bed is connected with the development of meanders and the lateral displacement of the channel (Fig. 75).

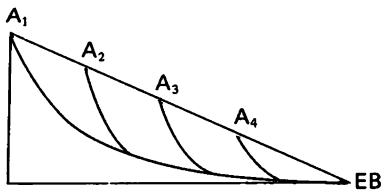
With the widening of the channel as a result of lateral erosion the rate at which the stream flows and its transportation property become diminished. This leads to a gradual decreasing of the erosive activity of a stream and the beginning of accumulative activity.

In the work of the most channel streams (particularly those that are permanent) three stages that succeed one another as the channel gradient becomes flattened are distinguished. The first is characterized by the predominance of river-bed erosion (*the youth stage*), as a result of which the transverse profile of the channel acquires a V-shaped form. In the second stage the river-bed erosion is replaced by the lateral variety of erosion (*the maturity stage*). The channel is widened and acquires a sinuous structure, while the transverse profile is gradually turned into a U-shaped form. The third stage of the development begins when the stream reaches the profile of equilibrium and when the attenuation of erosional processes becomes apparent. There emerges a very wide valley, within the confines of which the sinuous channel of the stream moves in an uncertain direction (*the senility stage*). With a large number of channel streams it is possible to observe all the three stages of development in different parts of the territory. The first stage in the upper parts, the second in the middle of the flow, and the third one in the lower regions.

The sequence of erosive activity of the water stream, that has been given above, can be disturbed as a result of the tectonic movements of the earth's crust or its

FIGURE 73. The profile of the river equilibrium:

EB – base level of erosion; A_1EB, A_2EB, A_3EB, A_4EB – successive profiles of equilibrium of an entrenching stream



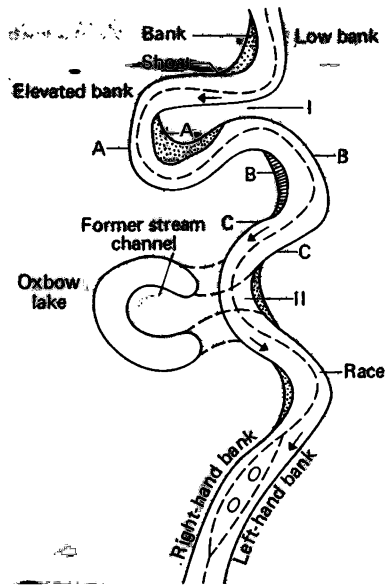
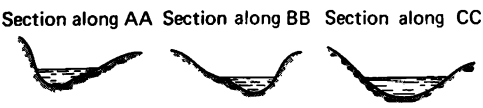


FIGURE 74. Rectangular river channel transform



own vibrations of the base level of erosion. The alteration of the relative position of the base level of erosion and the level of the head of the river change the gradient and the value of the water energy of the stream. An increase of the difference between the levels of the head and the base level of erosion leads to the generation of river-bed erosion, the rejuvenation of its already well-developed valley, i. e. to the entrenchment of a new, narrow and deeper valley into its wide platform.

The most important consequence following the rejuvenation of valleys is the formation of *terraces above the floodplain*, or the remnants of the previously existing valley floor with the cover of rock sediments deposited upon it, which have emerged as a result of the activity performed by the channel streams.

Depending on the abundance of water and the velocity of water flows in the stream, as well as on the geological structure of the locality relatively inconsiderable in size erosional forms appear: *erosional grooves* with the depth of up to 0.5 m, *hollows*, the depth of which is between 1 and 2 m, scours (up to 3-5 m in depth), and gullies. The longitudinal profile of grooves and hollows is in general parallel to the surface of the slope. The scours are characterized by a slightly concave longitudinal profile. What is common to all these forms is the V-shaped transverse section of the channel. In their further development the scour can be transformed into gullies, in which the more developed longitudinal profiles of the channel are found to be apparent.

In the formation of a large number of gullies their channel, which is called *thalweg*, can undergo all the stages of erosional development, viz. youthfullness,

FIGURE 75. Meanders and oxbow-lakes of plain rivers (Eastern Siberia) (photo by V. Rzhevsky)

maturity, and senility. Every year in the youth stage, owing to the backward erosion, the gullies gain several metres in length along the upward direction of the stream flow, while under favourable conditions (loose, easily washed-out rocks, abundance of precipitations, etc.) their elongation can measure several tens of metres. Simultaneously with their growth the gullies cover scours and hollows, which were once situated at some distance from the originally existing gullies. This results in the formation of a highly complicated ramified system of the erosional dissection of the surface. In some cases, when the depth increases, gullies uncover the water-bearing horizons of underground waters. This is when springs emerge on the river bed, which give rise to the constant acting channels. In the senile stage the edges of gullies become flattened and are not infrequently covered with vegetation, while the gullies themselves are converted into wide ravines.

In the mountainous regions the destructive work of temporary channel streams is more intensively manifested than in plain conditions, which is achieved at the expense of the marked velocity with which the water falls down from the slopes. In addition to this, as a result of the intensive thawing of snow and ice during the summer months and the abundance of atmospheric precipitations the mud and stone or *mudstreams* periodically emerge in mountains. Their formation is promoted by the presence in the mountains of stone material destroyed by weathering and unfastened by vegetation in the form of powerful hillside wastes on the slopes. At the time of heavy rainfalls and rapid thawing of snow these hillside wastes or taluses become oversaturated with water to such extent that they are washed down from the slopes in the form of mud and stone masses. A very significant factor in the development of the said processes finds its expression in violent earthquakes, which provoke the downfall, and the succeeding numerous aftershocks, which create a particularly dynamic ('agitated') state of the fragmental and clay water saturated masses. Mudstreams often lead to great catastrophies.

As a result of the erosional processes rivers form large depressions in the relief of the Earth's surface. They are called *river erosional valleys.* In the structure of river valleys three basic elements of the relief are singled out, viz. *the channel, the floor*, and *the slopes* or *banks.* The stream channel represents a relatively narrow

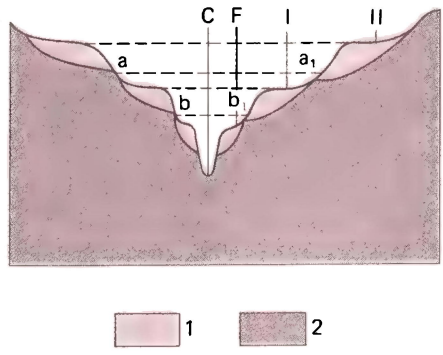


FIGURE 76. Cross section of a river valley:

C–channel; F–floodplain. I–the first terrace above the floodplain; II–the second terrace above the floodplain; a-a_1 and b-b_1–former floodplains, entrenched by the river; *1*–alluvium; *2*–bedrocks (limestones)

depression along which drainage takes place during the period of low waters. In the channel there occurs the most intense erosive and accumulative activity of the stream.

The floor of the valley is formed in the process of lateral erosion and meandering with the accumulation of sediments accompanying them. The greater part of river valleys is occupied by a floodplain, which is formed as a result of the accumulation of river sediments during freshets, when stream waters flow out of the channel and cover the adjoining parts of the valley floor. The slopes of the valley can have a most variable degree of steepness and structure that depend on the cyclicity of erosive activity of the river and the geological structure of the locality. The most important form of the relief pertinent to slopes is expressed in river terraces above the floodplain, which reflect the main stages in the development of the valley (Fig. 76). In addition to them on the valley sides we also find structural benches, ridges, and longitudinal structural terraces, i. e. forms of the relief connected with various degrees of the strength of rocks.

The destructive work of underground waters is reduced to their chemical interaction with rocks (dissolution, hydration, hydrolysis, oxidation, leaching) and the mechanical fracturing, and washing out by forces of moving stream. The transportation of the destructed material is carried out by underground waters mainly in the form of a chemically dissolved substance and to a markedly smaller extent in a suspended or dragged state.

The intensity of chemical decomposition depends on the chemical content of rocks and underground waters, the solubility and permeability of rocks, the relief of the surface and climate. The processes of chemical decomposition of rocks under the influence of underground and surface waters are called *karst processes*, or simply *karst* (after the name of the calcareous plateau in Yugoslavia). Karst phenomena are widely spread in a major part of the earth's crust (Fig. 77).

The most favourable rocks for the formation of karst are the halogen, sulphate, and carbonaceous ones. The penetration of water into these rocks leads to their dissolution and leaching, as a result of which cavities of various size and shape are formed. The formation of karst is promoted by the following factors: humid climate that enhances the rate at which rocks are dissolved; the even relief of the surface, increasing the period within which surface waters can exert their influence; the inclined position of rocks, providing the intensive circulation of water between the layers. One more factor that accelerates the formation of karst is the presence of mineral and organic acids in water.

In accordance with the characteristic features relevant to the occurrence of soluble rocks, the presence or absence of sheet water-resisting formations karst is subdivided into its exposed and underground varieties.

The exposed karst is developed in soluble rocks that come out onto the day surface. A purely superficial form in which karst manifests itself can be illustrated by grooves (furrows) and hollows that are referred to as *sinks*. The forms that are larger in size and more complicated in structure are *the sinkholes. The underground karst* is developed in soluble rocks that are deposited at a certain depth. These conditions give rise to the formation of vertical and inclined karst traverses, sinkholes and pits, as well as more complex systems of cavities called *karst caves*. They can be either horizontal or inclined, with one or several inlets,

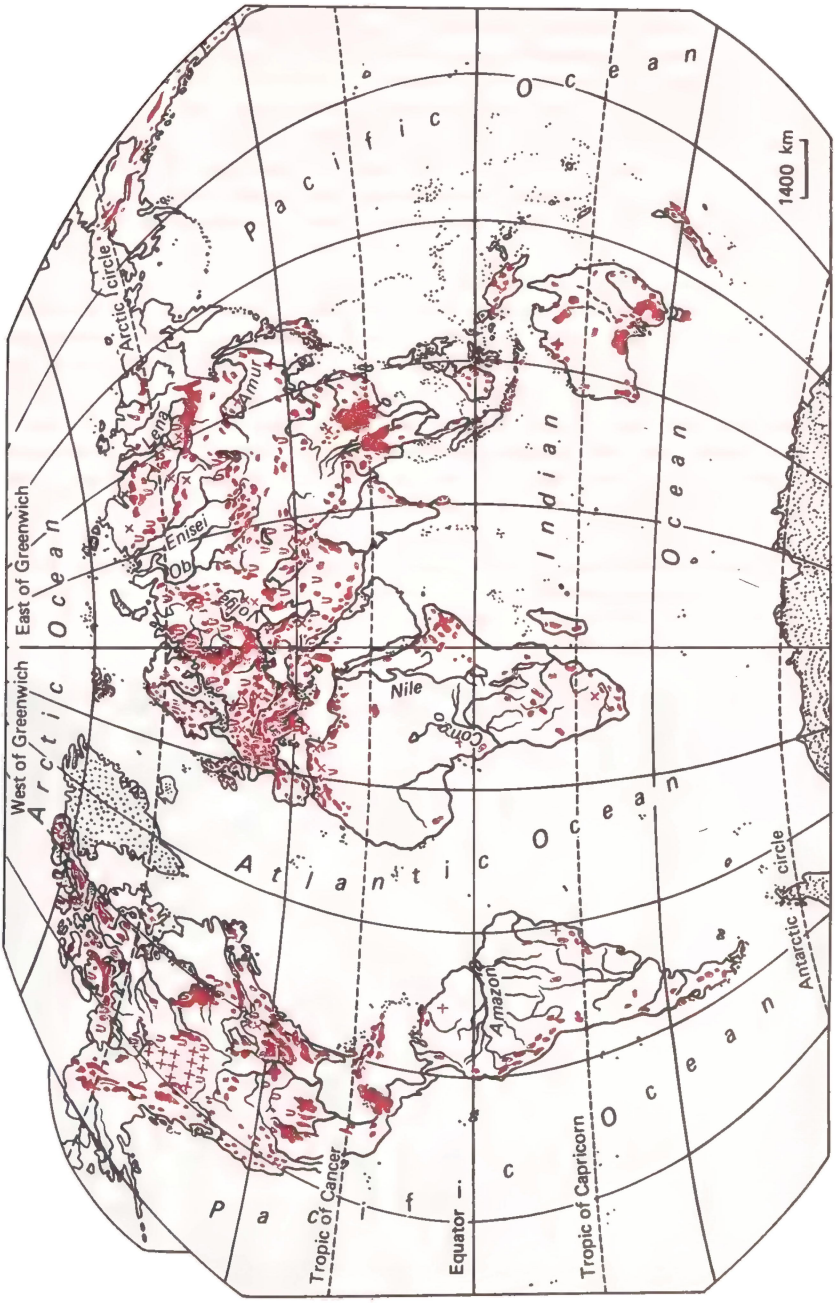


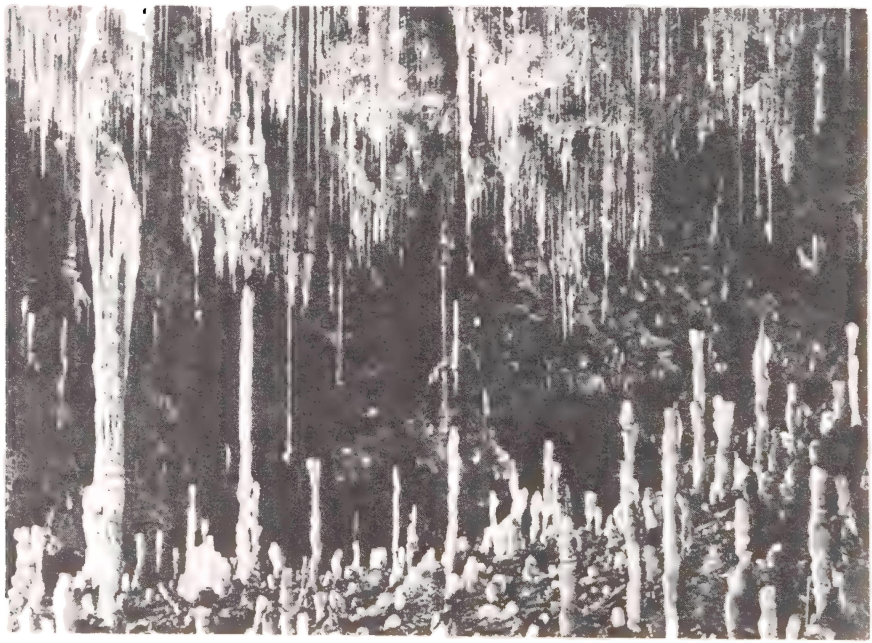
FIGURE 77. Map of the World

consist of a single elongated cavity or a whole labyrinth of transitions and ramifications, now narrowing into thin rents, now widening and becoming vast halls reaching hundreds of metres in length and as high as 20-30 metres (Fig. 78). Karst caves can function as channels for underground rivers that can hold enormous masses of water.

The arches of underground karst cavities can become unstable and collapse from time to time. When the position of karst cavities is not deep, the whole mass of overlying rocks right up to the day surface can be involved in the downfall which results in the formation of karst holes. The latter can be of different size and form ranging from small funnel-shaped depressions to large collapse pits and precipices.

The formation of karst, particularly in those cases when the rates of this process are great (the manifestation of more than 10 sinkholes in the area of 1 km^2 per year), has a negative effect on agriculture, construction works, and mining industry. In the case of open-cast mining it becomes necessary to remove the karsted rocks; in underground mining it is essential that they should be fastened by additional barrier pillars. Besides, karsting has a markedly negative effect on the quality of mineral resources that are removed, while karst waters deteriorate mining technology and the construction elements of workings. With the aim of prognosticating the formation of karst and establishing the conditions in which construction works and mining operations can be conducted on the territories susceptible to karsting, special normative recommendations have been elaborated in the USSR.

FIGURE 78. Karst cave



Alongside dissolution the underground waters in given conditions can perform mechanical work resulting in the destruction of rocks by means of gravity water force. This process has received the name of *suffosion.*

Suffosion is most widely spread in clay rocks (clays, loams, and loesses), and much less so in rocks characterized by arenaceous composition. The process of suffosion is most intensely manifested in the regions of arid climate, where underground waters circulate along the desiccation fissures and partings (joints) that were formed in clay rocks and wash out hard rock particles from them. As a result of the evacuation of hard constituents of rocks there takes place a disruption of their general structure and the stability of rocks, the formation of voids, and consequently there emerge subsidence and collapse of those rocks that are situated above the water-bearing horizon. There appear various forms pertinent to the subsidence of the surface relief, e. g. *suffosion sinks, wells, gullies, sinks* and *minor depressions.*

The Destructive Work of Snow and Ice. The geological activity of snow and ice consists in the mechanical fracturing of rocks and in the transportation of the destroyed material by the forces of moving masses. The snow that is easily movable and loose is taken up by the wind and performs destructive work of the type resembling corrasion. The turbulent snow drifts (snow storms and blizzards) fall upon the obstacles with the velocity of 200 km per hour and thus cause considerable damage.

Characterized by the properties of compactness and creep, snow can be accumulated in large quantities in the leeward parts of the uplands. Masses of thus collected snow on losing equilibrium can fall down to the foot of the slope in the form of snow avalanches. The enormous speed (up to 200 km per hour) at which these snow slips collapse produces powerful air movement of cyclonic character, which uproot the trees, push the fragments of rocks from the place, and destroy land-based housing buildings. Snow avalanches are of particularly frequent occurrence in the mountains.

The avalanches usually slip down the slopes, the angle of inclination of which is greater than 25°, though the most dangerous ones appear on the slopes with the steepness of 30-45°. In most cases snow avalanches slip down in spring, when meltwaters increase the mass of the avalanche and reduce friction. As a rule, avalanches move along the trenches, carrying away loose fragments of rocks and, at the same time, performing erosional activity. The size of transported rock fragments can reach several metres in diameter, while the total mass of hard material comprises $n \cdot 1\,000$ m^3.

The destructive activity of ice depends primarily on its type. The geological work performed by *drift ice* (river, lake, and sea) is carried out at the expense of the pressure exerted by glacial masses upon rocks in the period of complete freezing as well as of mechanical disintegration of coastal rocks during ice drifts. In the formation of ice fields in closed and half-closed basins the pressure becomes as high as 1 000 kg per 1 cm^2. This leads to the destruction of the coastal line.

In the course of ice drift blocks of ice are carried away by the current which results in that they destroy and polish the coastal sediments and entrench grooves in them. In the periods of complete freezing the fragments of rocks are

frozen into ice (pebble, sand, and boulders) which cover the floor in shallow water. At the time of ice drift the freezing-in rocks are often transported together with the ice from the place of their original bedding to considerable distances. The results of the destructive activity of drift ice find their expression in the formation of channels and river banks, the complicated dissected relief of the shores of lakes and seas (fiords).

Ground ice as compared with other types of ice is not an active geological agent participating in the destruction of rocks.

In the regions characterized by the development of perennially frozen rocks there can often occur underground waters under the frozen ground layer, which are found in a liquid phase and that usually have hydrostatic pressure.

Occasionally on account of the fissures that originate in the frozen ground layer pressure waters are intruded into the overlying horizons where they become frozen in the form of large lenses which rise the surface layers of rocks and are called *hydrolaccolites*. The hummocks that are formed above them are up to several tens of metres and more with a fairly steep slopes. They form the undulating relief of the surface.

In other instances pressure waters flow out onto the surface and give rise to the origin of ice bodies, or icings, the thickness of which reaches 5 m, while the area of their distribution measures several square kilometres. In summer, as a result of thawing of icings and hydrolaccolites, the pressure waters can abruptly break through with an explosion, as a result of which sinks of subsidence are formed, while fragments of ice and rocks are thrown out by the force of explosion beyond the confines of their own bedding.

The peculiar geological processes in those regions where ground ice is developed have very much in common with the karst phenomena as far as their results are concerned, and take place during the thawing of some of the parts of perennially frozen rocks. This process has been called *thermokarst*. In a large number of cases the thus formed subsidence forms of the relief are filled with melt and atmospheric waters and within these areas there appear lakes, bogs, or swamped meadows. The phenomena of thermokarst cannot possibly be unheeded especially in the building of engineering structures and when mining operations are conducted.

One of the main agents of denudation is glacier ice. The moving glaciers perform a considerable amount of destructive work and transport the material that has been destroyed. Glacial destruction has acquired the term *exaration*. As a result of the displacement of continental glaciers thick masses of ice smooth out the protrusions on the Earth's surface, and when they are melted the polished rocks of the bed remain. Moreover, during the movement of land ice a glacial corrasion takes place, as a result of which furrows and grooves remain on the smoothed-out surface of rocks.

In the course of exaration land glaciers create characteristic forms of the relief, e. g. furrows and basins, usually filled with water; asymmetrical smoothed-out hills called roche moutonnée; ice-dressed rocks, or concentrations of roches moutonnée; rocks called 'erratic masses' – hills, dislocated by glaciers, which are composed of yielding rocks. Under the pressure of ice there can take place

disruptions in the original bedding of rocks with the result that folds, overthrusts, and other glacial dislocations are formed.

The glacial exaration in mountainous regions is manifested in the glacial ploughing, smoothing out and alteration of forms in both within the confines of the alimentation area and in the run-off hollows that have previously been brought about by erosion. Under the activity of the moving masses of ice the erosional valleys are transformed into trough-like glacial valleys, or troughs proper, which have a wide gently concave bottom and steep slopes (Fig. 79).

The fragmental material is transported by masses of ice partly in a dragged state, partly frozen into ice, and partly on the surface of glaciers. The amount of material transported by glaciers reaches tens and hundreds of millions of tonnes; the distance over which transportation takes place can comprise hundred and thousands of kilometres.

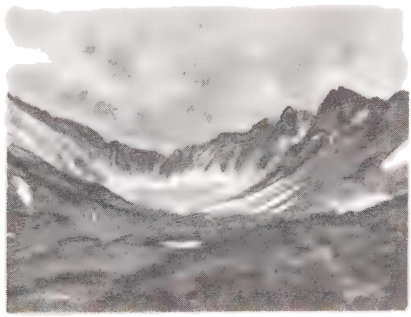
The Destructive Work of Seas and Oceans. It is particularly prominent in the littoral zone and within the shelf region. This is where all the types of water masses are in activity on mountain rocks, while the chemical composition of the medium promotes a fairly rapid course within which the reaction of dissolution takes place. In the zones of continental slope and ocean bed the destructive work is carried out mainly owing to the deep sea currents, water and gravitational processes (see below) and chemical decomposition in the conditions of oxygen deficiency.

As a result of the activity of waves and near-shore currents the rocks entering into the composition of the shore become gradually destroyed, while the coastal line recedes into the deeper regions of the continent (Fig. 80). This kind of destructive work performed by the sea is called *abrasion.*

The shores composed of crystalline rocks of magmatic and metamorphic origin are abraded very slowly as compared with the shores the composition of which is characterized by compact sedimentary rocks, where the disintegration is measured in centimetres or tens of centimetres a year. The abrasion is still more intense with the shores composed of loose rocks of either arenaceous or gravel and pebble composition. The rate at which the abrasion of these shores takes place is often measured in several metres a year.

The rate of abrasion is to a great extent influenced by the character of rock position. When the position of laminated rocks is inclined, the abrasion is particularly effective when the layers dip in the direction opposite to the sea, and

FIGURE 79. Trough valley



it is more weak when the layers dip towards the sea. The horizontally occurred rocks are abraded within a considerably longer period of time than the inclined ones. Rocks the dislocation of which is complicated and that are heterogeneous as far as their composition and physical and mechanical properties are concerned, create favourable conditions for selective abrasion, which leads to the emergence of an uneven rugged coastal line with numerous small inlets, caves, reefs, and grottoes (Fig. 81).

The intensity of abrasion greatly depends on the steepness of the bank slope and the adjacent coastal slope. The process leading to destruction is most prominent at steep shores, in the proximity of which the sea floor is characterized by a steep gradient. Conversely, in those places where the shore is very low, the incident wave gradually extinguishes its energy without producing almost any deteriorating effect, even if the coast is composed of loose sands and clays. As a result of the abrasion of shores an undermined or steep sea cliff (*abrasion bench*) is formed. Its foot is bordered on by a levelled-out, gently sloping platform, or *rock bench*. The part of rock bench situated in its submarine part covered with water at the time of storms and floods and formed by fragmental material is called *beach*.

The processes of abrasion and retreat of the shore with the sea level remaining unchangeable cannot proceed infinitely. As the width of rock bench increases,

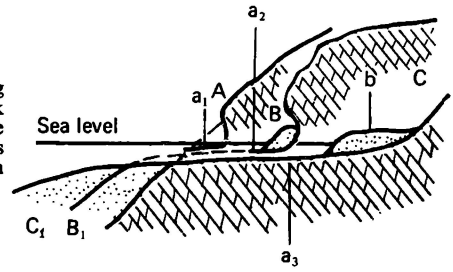
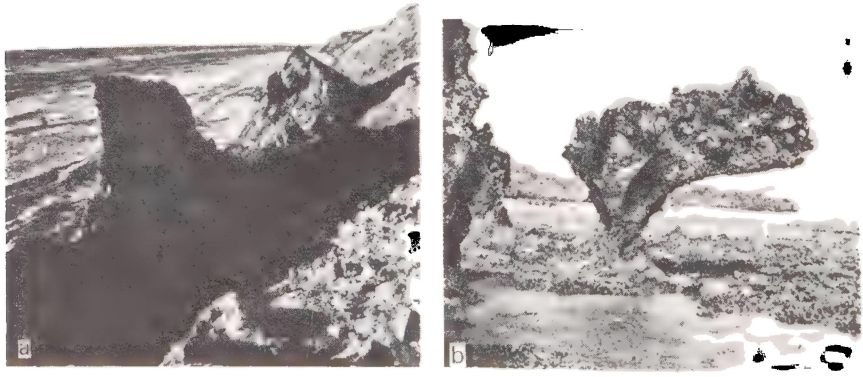


FIGURE 80. A diagram illustrating the stages of the retreat of the shore (according to V. Zenkovich):
A, B, C – different positions of the retreating littoral slope abraided by the sea; a_1, a_2, a_3 – rock benches, corresponding to different stages in the development of the shore; B_1, C_1 – different stages in the development of submarine aggradation terrace; *b* – beach

FIGURE 81. Marine erosion (*a*) and unusual relief forms as a result of marine erosion (*b*)



the destruction of the shore is retarded, since the incident wave will spend all of its energy on overcoming friction and will not be able to perform any abrasion. The resumption of abrasion can be brought about by tectonic processes, e. g. the lowering of the coastal surface, i. e. the advance of the sea. At the same time during the retreat of the sea rock bench can be found to be situated above the sea level, while the abrasive activity will result in the development of a new rock bench on a lower level.

The chemical decomposition of minerals and rocks within the medium of salt sea water has received the name of *halmyrolysis* and comprises dissolution, oxidation, hydration, hydrolysis, and other chemical and physical phenomena. The rate at which halmyrolysis takes place is influenced by temperature, pressure, density and the saline content of sea water, as well as the concentration of hydrogen ions.

The denudation activity of lakes, as is the case with sea basins, is reduced to the destruction of coastal benches and the near-shore parts of the floor (abrasion), and the carrying around of fragmental and dissolved material. The movement of water masses is manifested in the form of waves, currents, the turbulent mixing of water, and the water surges brought about by the wind. The greatest degree of significance is attributed to the movements caused by the wind. The force of waves and the depth of the roiling of sediments depend on the force of wind as well as on the area and volume of water basin. Lacustrine denudation has very much in common with marine denudation, though differing from the latter by small scales of manifestation.

Gravitational Processes of Denudation. The action of gravitational forces serves as a prerequisite for the emergence and development of gravitational and water and gravitational processes taking place on the continents as well as in the ocean floor.

The gravitational processes proper are developed on the slopes with the angles of inclination exceeding 30°, and predominantly in mountainous regions or in the plains characterized by extremely steep slopes. On the precipitous and overhanging slopes there occurs the process of *embankment*, or an abrupt collapse of rock masses in the form of individual lumps and large blocks, accompanied by the fracturing of the disrupted mass in the course of its downfall to the foot of the slope. The process involving the activity of talus, or *hillside waste*, in which separate fragments of rocks slip down the slope is pertinent to such slopes the steepness of which is insignificant.

The downfall processes, or *collapses*, most often occur along the newly formed scarps or markedly steep slopes which owe their origin to aqueous or glacial erosion, abrasion, or artificially created hollows. The most significant factors conditioning the formation of collapses are the steepness of slopes, complicated tectonic structure of the territory, and the intense jointing of rocks. Downfalls can be brought about directly by earthquakes, heavy rains, and lightning.

Rock falls often have a catastrophic character. History has recorded hundred of disasters connected with a sudden collapse of rock massifs. Downfalls and inrushes of unstable markedly fissured rocks in underground mining works are not less dangerous, when as a result of a mountain shock or earthquake there occurs a cave-in of the roof. Preventive measures directed at averting the

hazardous downfalls should primarily be concerned with the strengthening of mountain massif.

Talus processes are developed at a markedly slower rate than the downfalls, though they are spread much more widely. The material for the formation of talus consists of the mechanical products of physical weathering and those fragments of rocks that are ploughed out of the bed when the whole fragmental mass is displaced along the slope. It is not uncommon that taluses are found in mountainous regions. However, a large number of slopes of gullies and river valleys that are composed of loose and poorly stable rocks are also subjected to talus process.

On the slope talus is found to be in a state of dynamic equilibrium and moves slowly when there is a supply of new material from the upper regions. The inclination of the talus surface is near to the angle of repose of the material of which it is composed. The angle of repose for sand is equal to 33°, for loose loess and marls it is 25°, with schists the angle of repose equals 26-29°. The angle measuring 32° is characteristic of limestone, for gneiss it is 34°, its values for syenite and granite varies from 35 to 40°. The angle of repose can depend on the value of fragments, with other conditions being equal. In those cases when the angle of repose changes the material accumulated on the slope is liable to become unstable.

Many downfalls and taluses which begin their movement as an integral whole are broken up into narrow parts of fragments on the steep slopes. These particularly rapid flows are called fragmental avalanches. Some of the dry fragmental avalanches are mobile not only at the expense of the steepness of a slope, but also at the expense of air and fine particles contained in them. As a rule, dry avalanches are accompanied by a cloud of dust, while the impetuous air flow becomes so strong that it can easily fell trees and cause great damage to buildings.

Owing to the gravitational forces the slopes are known to be remarkable not only for rapid displacement of stone material of the type of downfalls and taluses, but also for slow flows that have acquired the name of *creep*. The thickness of the material in motion, including weathered rocks, can reach several centimetres and even metres. The average velocity of movement changes from fractions of one centimetre per year to 10 cm and more a week, depending on the steepness of slopes, climate, and the properties of rocks themselves.

The hydrogravitational processes take place on the slopes of various degrees of steepness, but most necessarily on condition of considerable humidification of displacing rocks. This group of processes comprises slumping and solifluction.

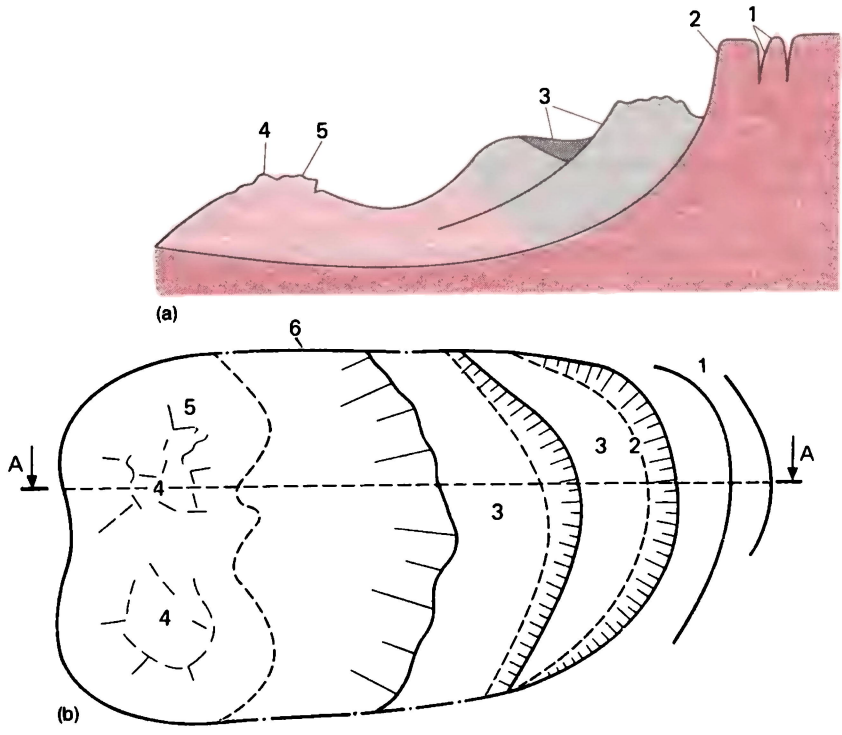
Slumping represents a process which presupposes the sliding of rock masses down the slope along the surfaces of break-off that appear in the slope massif. The landsliding surface, or the glide surface, emerges in accordance with the laws of mechanics in the period of break and gliding of collapsing masses of rocks. In cross section it represents a concave curve that has very much in common with a parabola, the lowest point of which is determined by the base level of slumping (Fig. 82). Gliding surfaces can be expressed by the boundaries of water-resisting rocks, the bedding planes of rocks that have different properties, tectonic fissures, and contacts with intrusions.

A considerable role in the development of slumping processes belongs to the waters of surface and particularly underground runoff. As a result of their activity there takes place a saturation of rocks by water occurring on the slopes, which results in the increase of their mass and the weakening of bonds between individual fragments of weathered rocks. In addition to this, as a result of wetting of the gliding surface by underground waters, friction becomes considerably diminished and, lastly, the displacement of rocks down the slope is facilitated by the hydrodynamic pressure of water that usually flows in the direction coinciding with that of the landslide.

In its movement down the slope the surface of the slumping massif forms a levelled-out platform, or *landslip terrace*, which is usually overturned in the direction of the slope part that has been destroyed. In the sinkholes that thus comes into existence there can accumulate meteoric precipitations which form lakes and swamps of inconsiderable size. The trees on the landslip terrace acquire an inclined position. If slumping occurs on repeatedly at various rates and in different directions, then the trees growing on the slope are found to be bent in

FIGURE 82. A diagram showing the structure of a landslide in section (*a*) and in plan (*b*):

1 – extension fractures; *2* – wall of tear; *3* - slumping bodies; *4* – swells of squeezing; *5* – heaving fissures; *6* – gliding fissures; *A-A* – line of section



different directions too. This phenomenon is known as an 'enebriated forest' (the forest growing on landslides).

The rate at which landslides move varies within considerably wide limits from the first centimetres per 24 hours to hundreds of kilometres per hour. The velocity of the landslide in Elma (Switzerland) in 1881 was as high as 320 km an hour. Most of the landslides move either slowly, or at a moderate rate.

The transporting property of slumping processes depends on the mass of rock that is transported by the landslide which is usually not great, covering from tens to hundreds of cubic metres. However, cases are not infrequent when catastrophic landslides are formed. They bring about enormous material damage and the loss of human lives. From time to time landslides of this kind emerge in different parts of the Earth – in mountainous regions as well as in the plains.

The largest landslide in the twentieth century occurred at the Usoi section in the Pamirs in 1911. It was preceded by a nine-point earthquake. The Usoi landslide the volume of which measured 2.2 km^3 covered the rocks of the slope and the snow at the depth of up to 500 m; it blocked the valley of Murgab River, as a result of which new Sarez Lake was formed. Its depth is approximately 500 m and the volume of the water mass is as great as 15 km^3. The most prominent landslides are considered to be the Yungai landslide in Peru (1970), which moved at the velocity of 200 km per hour; the Montar landslide (1974) also in Peru. Its volume was 1.6 km^3 and it gave rise to a large lake in the river valley of the same name; the Anchorage landslide in Alaska in 1964; the San-Fernando landslide (California, 1971) which resulted in that the dam was destroyed; the Vaiont landslide (Italy, 1960), which brought down 250 mln m^3 of loose and rock ground into the water basin and causing the death of about 3 000 people as a result of landslide waves that rushed from the dam down along the valley.

Solifluction represents a process of the slow flowing of surface layer of rocks under the influence of gravity and humidification. Typical solifluction processes are developed in the zones of perennially frozen rocks on the gentle slopes (2-6°) in water saturated clay and fragmental and argillaceous masses. In cases of solifluction the rate of movement is very small and is usually measured in centimetres, and seldom its value measures the first metres within the season.

As a result of solifluction various forms of the relief are formed. They are: *solifluction terraces*, *sintered bands*, *ramparts*, and *streams*. In mountainous conditions, owing to the processes of solifluction *altiplanation terraces* are formed. In the course of their development they truncate the peaks and merge into a single flat surface. This is what accounts for the origin of a large number of bald peaks in Siberia.

An absolutely different type of solifluction processes emerges on the surfaces composed of magmatic and metamorphic rocks, which in the course of weathering give rise to block jointing. On the slopes there accumulate disintegrated stone blocks, which move slowly downwards with the steepness ranging from 3-5 to 40-45°. These movements of the stone material have received the name of *rock streams* (in Russian they are called '*kurums*', the term having been borrowed from the Yakut language where it means 'stones'). Rock streams are displaced along the floor of ravines and hollows in the same way as stone

rivers and are extended over the distance from several metres to 1-1.5 km. The average rate at which rock streams move differs from 1-3 cm to 25 m a year. In the central part of the stream it is by one order higher than at its foundation. Rock streams are found in many regions of the USSR. Their study is highly important for the designing and building of railway track, highways, in conducting mining works, and the building of engineering structures in the proximity of the slopes.

Chapter 14 Accumulative Work of Exogenic Agents

Types of Sedimentary Differentiation of Matter

Sedimentation can occur as a result of the physical subsidence of material from the moving stream, when the gravity of transported substance is higher than the pressure of the medium that is engaged in transportation, as well as owing to the fallout of dissolved mineral substances, from true or colloidal solutions when ultimate concentration is achieved. An important role in sedimentation is allotted to the active life of animal and plant organisms.

The basic factors of sedimentation are physicochemical as well as physiogeographical conditions of the environment, which include climate, the surface relief, the locality where processes take place (surface of land or basin floor) and their thermodynamic parameters, conditions in which organisms exist and others. Their whole sum total materialized in the sediment or rock gives rise to what is generally known as *facies.*

Facies of different orders are distinguished, *Macrofacies* comprise genetic groups of facies – continental and marine varieties. *Mesofacies* include eluvial, deluvial, proluvial, alluvial, lacustrine, palustrine, glacial (the group of continental facies), those of the coastal zone, shelf, continental slope, and ocean floor (the group of marine facies). *Elementary facies* are the constituents of mesofacies.

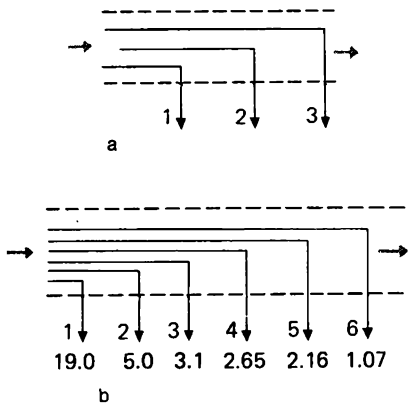


FIGURE 83. Mechanical differentiation (a diagram):
a – according to the coarseness of fragments (*1* – conglomerates; *2* – sand; *3* – clay); *b* – according to density with the value of fragments being equal (*1* – gold, *2* – pyrite, *3* – chromite, *4* – quartz, *5* – graphite, *6* – amber)

For instance, alluvial facies are divided into channel, floodplain, and deltaic varieties; the inshore and marine type, includes facies of beaches, inshore bars, spits, etc.

Depending on the character of those forces that lead to the segmentation of substances, mechanical and chemical types of differentiation are kept apart.

Mechanical differentiation represents the sorting of fragmental material in the process of its deposition in definite sequence, determined by the value, density and form of the transported fragments, and the characteristic features of the environment together with other factors (Fig. 83).

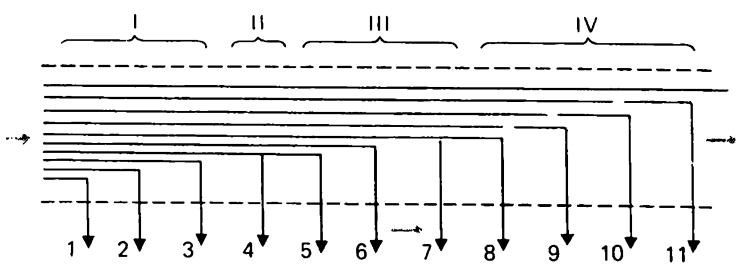
Chemical differentiation is the process which involves a consecutive deposition of mineral substances that are transported in the form of true or colloidal solutions. The main factors conditioning chemical differentiation are different concentrations of hydrogen ions in water solutions (hydrogen index, pH) and a different redox potential (Eh) in the zone of sedimentation.

Waters from which the fallout of sediments takes place can have acid (pH = 1-7), neutral (pH = 7) or alkaline (pH = 7-14) reaction. There is a distinct increase of pH from the place where mineral substance is decomposed in the direction of fluvial streams and further towards sea basins. It is in this direction that a successive sedimentation of mineral substance actually takes place (Fig. 84).

In natural conditions physical and chemical types of differentiation usually occur at one and the same time, overlapping each other. One form of the differentiation of sediments is found very seldom (a well sorted quartz sand, pure limestone, and rock salt).

Among the products of accumulation several types of sediments are distinguished according to their origin and composition. They are: *the terrigenous sediments*, which were formed at the expense of products of the mechanical disintegration of rocks; *chemogenic* sediments that are precipitated from the water medium chemically; *organogenic*, or *biogenic* sediments, that emerged at the expense of the active life of animal and plant organisms. Moreover, *volcanogenic and sedimentary formations* are also singled out. They originate as a result of the occurrence of products of sub-, and super-marine volcanic eruptions in sea conditions.

FIGURE 84. Chemical differentiation according to L. Pustovalov (a diagram): I – oxides; II – silicates; III – carbonates; IV – sulphates and halogen salts. *1* – Fe oxides; *2* – Mn oxides; *3* – SiO_2; *4* – Fe silicates; *5* – ferrous salts; *6* – $CaCO_3$; *7* – dolomite; *8* – $CaSO_4$; *9* – NaCl; *10* – KCl; *11* – $MgCl_2(MgSO_4)$



The relationship of the main genetic types of sediments and their character in different regions of the Earth's surface are not identical and are primarily related to climatic zonality. In accordance with the physiogeographical conditions of sedimentation medium four types of the accumulative process are distinguished: *glacial, humid, arid,* and *effusive and sedimentary.* The glacial type of sedimentation includes all the areas of continents with a thick glacial cover. The formation of this type is characterized by processes of mechanical sedimentation. Humid zones, which are distinguished by an enhanced degree of humidification and temperature, are characterized by the predominance of chemical and biochemical sedimentation processes. In arid conditions the principal role belongs to mechanical (eolian) accumulation. Effusive and sedimentary variety is typical of small areas in the zone of volcanic eruptions.

Terrigenous (Mechanical) Sediments

The principal sources giving rise to terrigenous sediments are products of physical (often chemical) weathering, denudation and hard products of volcanic activity. Terrigenous sediments are mainly formed as a result of the work performed by the wind, the waters of surface runoff, sea waters, the waters of oceans and lakes, snow, ice, and gravitational processes.

The Accumulative Work of the Wind (Eolian Deposits). The deflation products transported by the wind (sand, clay particles, and dust), as well as the elements of organic origin (volcanic ash and cosmic dust), falling out of the air flow give rise to eolian deposits. In the composition of masses of eolian sands it is often possible to find a peculiar cross bedding as a result of the change in the direction of wind.

In the marginal parts of deserts, and in the steppe regions and hillsides adjacent to them, we have the formation of *loess deposits.* Loess is non-stratified, porous, light-yellow rock, in the composition of which there is a predominance of dust particles of the size ranging from 0.05 to 0.1 mm (over 50%). It is composed of silica, alumina, calcium carbonate, and organic substances. During the process of mechanical wearing loess, in a dry state, is transformed into finely dispersed dust, while after humidification it becomes sticky mud. In contrast to sand loess is less loose, and hence in the course of deflation and water erosion it becomes remarkable for the emergence of hollows and gullies with very steep and almost precipitous slopes. The thickness of loess masses developed in Chinese People's Republic, Central Asia, and in the Ukraine differs from several metres to 1000 m and more.

Under the favourable conditions the shifting masses of sand with pulverized and clay particles form eolian formations of quite different forms on the Earth's surface, e. g. sandy hammocks, dunes, barkhans, and ridges (Fig. 85). *Sandy hammocks* are formed in practically the same way as snow drifts during the chaotic movement of wind when the material is blown together near various obstacles. *Dunes* are defined as elongated asymmetrical hills with rounded tops and more gently sloping weathered slopes. Their height varies from 5 to 30 m, sometimes reaching 100-200 and even 500 m. *Barkhans* represent hills, which, in plan have a crescent form, the horns of which are turned in the direction of the

wind. The weathered slope of barkhans varies from 3 to 15 m, and sometimes is as long as 80 m and more.

Under the influence of wind all the eolian forms of the relief have the property of being displaced at the expense of particles that are blown off from the weathered slope, and their accumulation on the leeward side. The rate at which dunes and barkhans move is between 6 and 25 m per year. In the course of their displacement eolian formations block up settlements, railway tracks, irrigation systems, etc. According to the data available at the United Nations Organization the moving sands of Sahara destroy thousands of acres of fertile lands every year, with the damage amounting to hundreds of thousands of dollars. With the aim of hindering the movement of sands vegetation is being planted and bitumen emulsion, together with the creation of artificial barriers, serve the same purpose.

These forms of eolian deposits are widely developed in desert regions, as well as on sea shores, and in the valleys of large rivers. In the USSR regions of this kind include the deserts of Kara Kum and Kyzyl Kum, the coast of the Baltic Sea and the Gulf of Finland, and the river valleys of Oka, Dnieper, and Don.

The Terrigenous Sediments of Temporary Surface Streams. The accumulative work of surface wash-out waters is manifested in the formation of accumulations of fragmental material in the lower part and at the foot of the slopes. The term which is applied to it is *deluvium.* It represents deposits of poorly sorted finely fragmental material with very thin lamination, and a characteristic overlap form of occurrence (deluvial trains). In the composition of deluvium there is a predominance of loams and sandy loams diversely enriched by more prominent fragments (sands, gruss, and rock debris).

The structure of deluvial masses can be remarkable for the presence of

FIGURE 85. Dune in section (*a*) and barkhan, view from the top (*b*)

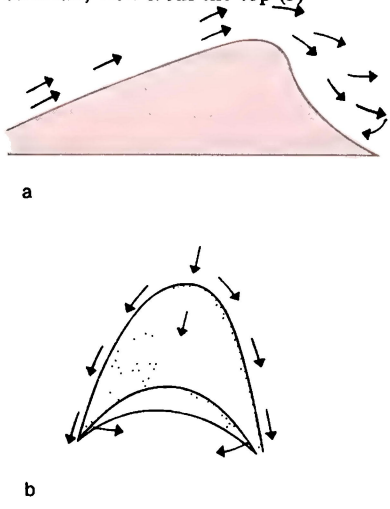
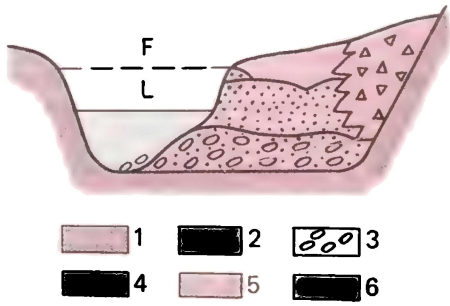


FIGURE 86. A diagram showing the distribution of alluvial facies:

1 – bedrock; *2* – deposits of reach facies; *3* – deposits of facies near the channel line; *4* – deposits of facies characteristic of littoral shoals and spits; *5* – deposits of floodplain facies; *6* – deluvial deposits; *L* – low-water level; *F* – flood level



zonality, which finds its expression in the regular distribution of material according to the coarseness of fragments and density with respect to the surface of the foot of the slope. The fine material is transported by the waters into the peripheral part of the deposits. The thickness of deluvial deposits depends on the height and steepness of the slope, the strength of the rocks entering into its composition, the character of the water stream action and is connected with the structure of the deluvial mass. In the upper part of the deluvial sheath the thickness varies from several centimetres to 1-2 m. Then, at the foot of the slope it markedly rises and reaches 10-15 m; in the lower part of the train it goes down to zero. Deluvium is widely spread in the plains, and on the hillsides, watersheds, edges of river valleys, though it can also be found in mountains, where it is confined to more gentle slopes.

The Accumulative Work of Channel Surface Waters. Temporary fluvial streams (the gully and valley varieties) deposit the fragmental material transported by them near the mouth and form accumulations in the form of detrital cone. The latter reach especially great dimensions in piedmont lowlands. The deposits of detrital cone have received the name of *proluvium.*

From the apex of detrital cone to its foot the coarseness of fragmental material changes from pebbles and rock debris to sandy loams and loams. In the periphery itself there occasionally takes place the deposition of clay material. Proluvium is predominantly characterized by a poor sorting of the material and insufficient roundness of fragments. The thickness of proluvial deposits in the central part of detrital cone varies from the first metres to 15-20 m. The same can be said of the length of detrital cones which varies within a wide range and during powerful mudstreams can reach 1-3 km and more.

As early as in the primary stages of their development the permanently functioning streams deposit fragmental material in certain areas. As first deposits are unstable and when the volume of water and rate of flow are increased, they can again be displaced down the stream. But, as the profile of equilibrium is worked out and the valley of lateral erosion is widened in the river channel there accumulate more and more stable sediments. The deposits that are accumulated in river valleys as a result of the work of water stream are called *alluvial deposits,* or simply *alluvium.*

The conditions relevant to the deposition of alluvium are not the same in different parts of the river channel. Within a single cycle of erosion four zones, distinguished from each other by the character and granular composition of alluvial deposits, can be singled out. They are: *the zone of reaches, channel line zone, the coastal shoal zone (spit zone),* and *the floodplain zone.* The first three zones correspond to the channel parts with permanently functioning water streams; the floodplain zone is confined to the parts of the valley, filled with water during the freshet period (Fig. 86).

In the zone of reaches there is an accumulation of coarse-fragmental material, which remains from the washout and evacuation. In the littoral zone, due to the instability of the hydrodynamic regime, the fragmental material with the lenticular and diagonal lamination, and with the variable degree of coarseness and compactness of particles, is deposited over short distances. In the zone of coastal shoals it is possible to find well sorted arenaceous and pebble-gravel

deposits. The floodplain deposits are mainly composed of finely fragmental material.

In mountain rivers the difference between floodplain and channel alluvium does not actually exist. In the deposits there is a predominance of the material with properly rounded fragments. Small lenses of gravel and coarse sand are not infrequent either.

Exceptionally favourable conditions for the accumulation of alluvium are created in the estuarine parts of the river where the channel gradient is more gentle and the flow rate is slow. This is where there takes place an intensive accumulation of the material transported by the river at the expense of which *deltas* are formed (the term coinciding with the pronunciation of a letter in the Greek alphabet), *submarine ramparts*, and *bars*. River deltas are constantly increased in size, and move in the direction of the sea with the rate from the first metres to 100 m a year. Thus, Don River extends itself towards the sea 11 metres every year, while the delta of Volga River captures up to 170 m of the Caspian Sea within year.

The normal total thickness of alluvial deposits of mid-channel rivers fluctuates from 10-15 to 30 m. The thickness of alluvium in Volga River comprises 20 m, with Moskva River it is 12-14 m, 6-8 m are characteristic of Dnieper River. The alluvium in mountain rivers usually reaches 3-5 m.

The Accumulative Work of Snow and Ice. Show is a remarkable precipitant of hard particles suspended in the air, which were formed as a result of technogenesis, volcanic activity, and at the expense of meteoric dust. Every year up to 1.5 mln m^3 of hard sediments from the atmosphere are accumulated in the regions of seasonally frozen ground. A greater amount of fragmental material is still formed in mountainous regions when snow avalanches come down. Fragments of rocks captured by avalanches are accumulated in the form of detrital cones which resemble mud flows. The avalanche deposits are characterized by a total absence of sorting out and roundness of fragments.

The accumulative work of ice manifests itself either in the direct deposition of fragmental material which has been brought by glaciers, or in the deposition of products that were reworked by melt glacial waters. Deposits of the first type are called *moraines*, those of the second are referred to as *fluvioglacial formations*.

Moraines are formed at the expense of the supply of fragmental material from the slopes of glacial valleys and as a result of destruction and transportation of rocks underlying the glaciers. The composition of moraines includes fragments of rocks of quite different size – from large blocks to small sandy and clay particles. In accordance with the position of fragmental material within the mass of the moving ice moraines are distinguished as either *basal*, *superficial*, or *internal mobile ones*, while the superficial variety lends itself to a further subdivision into those that are *lateral* and *the medial ones* (Fig. 87). All the types of mobile moraines are found only in mountain glaciers. Superficial and internal moraines are not characteristic of inland ice, while basal moraines are not typical of drift ice.

In thawing of ice mobile moraines give rise to deposits among which *basal* and *terminal moraines* are kept apart as two distinct types. The most widely spread basal moraines comprise the whole fragmental material transported by the

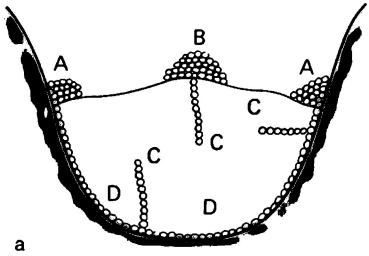
glaciers and cover vast areas. They are characterized by surface position, the absence of lamination and the sorting of material according to size. As the distance from the denudation area becomes greater the quantity of the dust-like material in a moraine increases, while the number and size of boulders are diminished. The thickness of a basal moraine comprises from 5 to 15 m and seldom reaches 30-50 m.

Peripheral, or *terminal, moraines* represent ramparts and ridges that fringe the glaciers. In their formation a substantial role is played by meltwaters, which evacuate the fine material, enriching the moraine with large fragments. The thickness of terminal moraines can reach 100 m and more. The terminal moraines are of great historical and geological significance, since they mark off the boundaries relevant to the extension of glaciers and the stages of their recession. In the European part of the USSR there are five large terminal moraines.

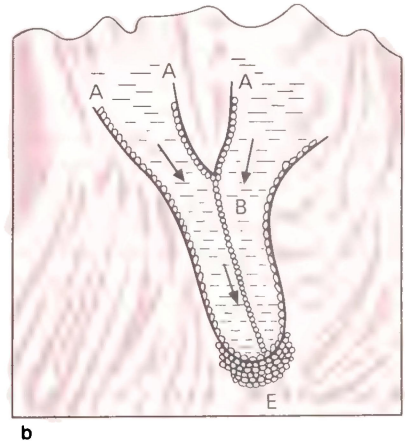
As the process involving the thawing of glaciers progresses meltwaters form specific types of *aqueoglacial deposits* in the very body of the moraine itself as well as beyond its confines. The said formations are classified into fluvioglacial and lacustrine and glacial deposits.

The fluvioglacial formations have some features common with alluvium. They are represented by accumulations of markedly rounded and rewashed sands, gravel, pebble-beds, and boulders, which form fairly thick masses (their height ranges from 20 to 50 m, the width is between 100-300 m, and in places as great as 1-3 km; their length measures scores of kilometres), the form of which is very much the same as the sinuous ramparts and ridges that are approximately situated along the direction in which the glacier moves. These masses have been called *eskers.* In most of them we can find a well developed lamination of both the horizontal and oblique varieties, which is much the same as the lamination of the

FIGURE 87. A diagram illustrating a moraine in the cross-section of a glacier (*a*) and in plan (*b*).
Moraines: *A* – lateral; *B* – medial; *C* – internal; *D* – basal; *E* – terminal



a



b

streams. Eskers are widely spread in Finland, Karelia, the Leningrad and Novgorod regions, and in the Baltic Sea region.

Glacial meltwaters in rewashing moraine deposits evacuate a considerable amount of fragmental material outside the boundaries of the glacier. Cases are not infrequent when before a glacial front a flat plain is situated. This is when meltwaters are broken down into numerous nonpermanent streams wandering upon its surface, while their deposits form a continuous cover of fluvioglacial fragmental material. Deposits of this kind are called *outwash plains*. Their structure is characterized by the predominance of well washed and sorted sands, usually with an admixture of fine pebbles and boulders. The thickness of outwash plains reaches 3-5 m and seldom more. In the direction towards the glacier the sands in outwash plains are replaced by gravel and pebble deposits, while in the direction of the periphery the replacement is accomplished by sandy loams.

The lacustrine and glacial deposits are represented by fine and thin fragmental material without any admixture of organic substance. Periglacial lakes are especially characterized by the deposits of fine fragmental and horizontal bedded sands and clays with a perfectly expressed annual, or ribbon lamination. The origin of lamination is accounted for by the seasonal cycle of fragmental material accumulation. This results in that there emerge the so-called *varved clays*, in which a couple of interlayers (sand and clay) make up the annual layer. In the fossil masses of varved clays there are sometimes hundreds of annual layers and more, which makes it possible to determine the age of the whole mass.

The Accumulative Work of Seas and Oceans. Sedimentation takes place within the whole area of the ocean and sea beds, though it is more intense in the coastal zone and in the shelf zone. Every year the World Ocean receives billions of tonnes of fragmental material of which 16.5 bln t are supplied by rivers; 1.6 bln t are accounted for by the glaciers. Abrasion gives 0.5 bln t, while 2-3 bln t are 'contributed' by volcanic eruptions.

Specific conditions in the *coastal* (littoral) *zone* serve as a prerequisite towards the formation of various sediments with a high degree of variability of their composition over short distances and within inconsiderable periods of time. Three types of coasts are distinguished. They are: *the abraded shore*, *the stable coast*, and *the accumulative coast*, each of which is characterized by its own type of deposits.

The character of sedimentation in *the shelf region* is influenced by the hydrodynamic regime of the basin and the relief of the floor, as well as by the quantitative and qualitative composition of rock fragments brought from the continent. The terrigenous sediments in the shelf region are represented by properly sorted out and rounded minute peble-beds, sands, and silts. In the formation of sediments within continental seas in most cases there is a decrease in the coarseness of fragments as the distance from the shore becomes reduced. The transition from one granulometric composition of fragments to another is gradually accomplished and occurs at different depths.

One of the sources of shelf deposits finds its expression in colloidal particles supplied by the rivers and falling out into the sediment with the formation of sea oozes during the process of coagulation. The rate at which the sediments are

accumulated in the shelf region in marginal and inland seas comprises about 6 mm on an average within the period of a century. In some cases, this rate is somewhat greater. The thickness of contemporary terrigenous sediments changes in accordance with the type of sea basin and makes an average from 0-10 to 50 m.

The sediments of *continental slope* are characterized by a prominent heterogeneity of its composition. Among them there is a predominance of fine-grained terrigenous silts and products of volcanic activity (sands and ash). Depending on their conposition terrigenous silts are different in colour and are consequently distinguished as either blue, red, or green silts.

The blue silt is most widely spread. It consists of the thinnest silty and clay particles with small admixture of calcite in the form of shells of microscopic planktonic organisms and an almost imperceptible formation of pyrite. Its colour is conditioned by the formation of sediments in the reducing medium and a large quantity of organic substances. In the proximity of the coasts of tropical regions continental waters wash down products of lateritic weathering into sea basins, which are deposited on the continental slope and give rise to the formation of red silt. Its propagation is more restricted than that of the blue variety and is found near the coast of South America, Africa, and India. In a number of regions we find the development of yellow silts (at the expense of the weathering of loess) and the green ones, or the glauconitic silts.

Among the sediments of *the ocean bed* the deposits that are widely spread are those of the so-called red oceanic clay, which represent fine clay sediment of brown or brick-red colour. The formation of red clays takes place at the expense of the accumulation of eolian, volcanic, and meteoric dust, as well as the insoluble organic remains. Hence, one would not err to consider red clays as not purely terrigenous, but polygenous formations instead. The accumulation of sediments in the region of ocean floor takes place very slowly, the velocity being 0.5-1 mm per one hundred years.

The change of facies conditions of sedimentation in seas and oceans, which occur mainly owing to the oscillatory movements of the earth's crust, results in the formation of *transgressive and regressive sedimentary masses.* What is typical of them is a clear-cut zonality in the distribution of fragmental material.

Terrigenous sediments prevail in most of the lake basins. They are formed at the expense of the material that is supplied by rivers, and the products of the destruction of the shores and the floor of lakes. The main role in them belongs to sand and clay deposits, which often have a characteristic thin horizontal bedding. The coarse-fragmental material, such as pebbles and gravel, is less widely spread.

The Terrigenous Sediments of Gravitational Processes. The deposits resulting from downfalls are distinguished by a total absence of sorting and roundness of fragmental material and its chaotic agglomeration at the foot of the slope. The composition of taluses is remarkable for the predominance of rock detrital, and less often block and gruss fragments of rocks. The fragments are not rounded, though they are occasionally found to be considerably rubbed. Taluses are characterized by a certain sorting of fragmental material with the preponderance of large fragments in the lower part of the shelf with a gradual decrease in their

size up the slope. The newly formed taluses are usually found to be not consolidated. In the older varieties of talus fragments can be fastened together by sand and clay material or some mineral cement.

Downfall and talus deposits in highlands often overlap each other, thus forming *colluvial deposits*, which cover the piedmont parts of mountain slopes with a continuous mantle. The knowledge of the characteristic features of these deposits is highly important when mining works and geological surveying are conducted. As ancient, now turf-covered taluses and downfalls are found to exist, it becomes important to discern them by their outer features in the relief. The passing of mining works in these old formations can cause the recurrent movements of fragmental material. What presents the main hazard is the moistened masses of colluvium by either natural or industrial waters. As a result of humidification and when opening up in the course of mining operations. they begin their movement, which can have catastrophic consequences. In the case of landslides phenomena bodies of the same nature are formed. They have the form of an elongated hill or a ridge extended parallel to the slope.

Within the zone of solifluction accumulation at the foot of the slope where the main mass of the material is uploaded we have the formation of *spurs*, while with the increase in the gradient and a more heterogeneous composition of surface rocks there emerge *solifluction terraces*. The foundation of solifluction deposits is composed of sandy loams with inconsiderable admixtures of rock debris and small blocks of more stable rocks. In the zone of active drainage one can often find this material to be characterized by banded flow structure. It should also be mentioned that spurs are remarkable for the preponderance of sandy loams with an irregular distribution of rock debris and blocks.

The Practical Value of Terrigenous Sediments. The processes of mechanical sedimentation are connected with the formation of many types of mineral resources. This includes the natural building materials (sandy and gravel deposits of the seas, alluvial and beach pebble-beds and sands), used in road works, as fillers in concrete, in the form of ballast, etc. as well as the raw-material for glass and ceramic industry (quartz sands of alluvial origin, the clay deposits of lakes and seas), and the raw material employed in metallurgy (refractory and high-melting clays of fluvioglacial origin). Terrigenous sediments are connected with the formation of large placer deposits of diamonds, gold, platinum, zircon, rutile, ilmenite, cassiterite, wolframite, precious stones, and others.

Chemical Sediments

Chemical sediments are exclusively formed in water medium at the expense of mineral substances, which are found in a dissolved state and precipitate from the solutions when the physicochemical conditions of the medium change. Natural solutions, from which chemical sediments are formed, can be either true or colloidal.

The precipitation of dissolved mineral substances takes place when the solutions are oversaturated as a result of the evaporation of water, changes in temperature and pressure, and pH and Eh change of medium. In the process of chemical weathering and in the presence of humus acids a number of unsoluble

substances are transformed into colloidal solutions and are transported by water streams. In mixing of colloidal solutions with the true ones the coagulation of colloids and the precipitation of sediment take place. Besides, in the precipitation of mineral substances from colloidal solutions an important role is attributed to biochemical processes.

The principal exogenic agents in the formation of chemical sediments are underground waters, the waters of lakes, swamps, seas, and oceans. The rate at which chemical sediments are accumulated and the thickness of deposits depend on the amount of the mineral substance dissolved in water medium and the length of time within which favourable conditions are preserved in the processes of sedimentation.

The Chemical Sediments of Underground Waters. The accumulation of chemical sediments is accomplished either by means of filling finished fissures, voids, and cavities or by metasomatic replacement of the enclosing rock, or during the outflow of underground waters on the Earth's surface in the proximity of drainage.

In the process involving the accumulation of a mineral substance in subterranean conditions loose and markedly fissured rocks occurring on the border with compact, impermeable rocks, as well as karst rocks with their caverns and cavities, prove to be most favourable. Accumulations of sediments in the form of individual or interconnected pockets, lentils, and nodules are formed in loose rocks. In the fissures and voids of compact rocks there are systems of veinlets and streaks with coatings and crusts that appear on the walls of fissures.

In large karst cavities chemical sediments compose various sintered forms that grow on the arches, walls, and bottoms of the said cavities. Arched formations in karst cavities have received the name of *stalactites.* They can have shape of mineralized icicles, curtains, and fringes. Basal formations, or *stalagmites*, have a conical or a more complicated columnar form (see Fig. 77).

Stalactites and stalagmites can be of various size, ranging from 5-10 cm to several metres in diameter. If a stalactite or a stalagmite were cut up into two equal halves, it would be possible to see rings in the cross-section strain that resemble the annual rings of trees. It has been established that within the period of one year two rings differing from each other in colour are formed. This enables the scientists to determine the age of stalactites and stalagmites. Thus, the gigantic stalagmite in the Carlsbad cave (USA) with the diameter of 4.9 m, as was shown by the computation of rings, has been accumulated within the period of sixty million years, while the calcareous stalactites in the Crimea, the diameter of which measures 50 cm, have been formed in the period of two thousand years.

Of great practical value are the deposits of underground waters near the ore deposits, particularly the sulphide ones. The fissure and karst sulphate waters redeposit the ore substance, thus forming new accumulations at a certain distance away from the primary ores. Not infrequently these new formations consolidate the loose weathering products which enclose the orebody of rocks. These formations can be exemplified by the consolidation zone of copper sulphide deposits.

The chemical sediments of underground waters near the places of drainage

upon the day surface are particularly developed on the slopes and floors of valleys. At the place of the outcrop of underground waters, saturated with carbonaceous substances on the surface, calcareous tuffs or porous formations can be formed. They often contain organogenic remains. The ouflows of thermal calcic carbonate waters are connected with the formation of *travertines*, or calcareous deposits that are more solid and well crystallized as compared with tuffa.

The Chemical Sediments of Lakes and Swamps. The lakes of arid climate are mainly characterized by the sedimentation of halides, sulphates, and carbonates by means of the evaporation of solutions and the enhancement of the concentration of dissolved substance. Depending on the composition of sediments lakes are classified into sulphate, halide, and soda types. In the lakes of sulphate type the first to precipitate are carbonates (limestones and dolomites), then follows the formation of interlayers and lenses of gypsum and anhydride with halide formations completing the process of sedimentation. In the lakes of halide type (Elton and Baskunchak) sodium chloride is precipitated in the dry period of the year. In soda lakes (Mikhailovskoye and Petukhovskoye in the Kulunda steppe), the precipitation of sodium carbonate (soda) takes place in the winter months.

Large lakes of the humid climate, and those of the fresh and poorly mineralized varieties are mainly characterized by the accumulation of terrigenous material; river waters are supplied by the products of chemical weathering in the form of colloidal solutions (hydroxides of iron and aluminium). In shallow-water coastal areas there takes place the coagulation of colloidal solutions and the formation of ferriferous sediments, while in the tropical and subtropical zones there also occurs the formation of aluminiferrous sediments. At the expense of the supply of calcium carbonates by underground waters there takes place the formation of sediments of chalk and marl.

Specific conditions of sedimentation exist in marine lagoons both of salt water and fresh water types. In salt-water lagoons chemical deposits of gypsum, anhydrite, mirabilite, and rock salt are formed. The sequence of their sedimentation is conditioned by the salinity of water. Terrigenous and organogenic sediments are developed in fresh-water basins.

In the reducing medium pertinent to palustrine conditions, as well as in lakes, the formation of chemical sediments can be found. This primarily concerns the ferrous compounds of iron and manganese (marsh ores), the sedimentation of which is promoted by a rich palustrine vegetation. The region that is most remarkable for swamps of this kind is Polesye.

The Chemical Sediments of Seas and Oceans. Depending on the facies conditions chemical sediments in seas and oceans are formed at a different rate and are various as far as their composition is concerned. Chemical sediments in the coastal zone are formed rather seldom. They are found in the coastal belt of seas of hot and dry climate, the water of which contains a considerable amount of lime. In the process involving its precipitation from water the formation of calcareous sediment of oölitic structure takes place. Calcareous oölites emerge at the expense of the deposition of lime round minute particles that are found in water in a suspended state and serve as the centres of crystallization. Oölitic

calcareous sediments of this kind are nowadays formed at the shores of the Red, the Caspian, and the Aral seas.

In the shelf region chemical sediments are characterized by a great variety. In a hot climate and in conditions of shallow sea we have the formation of calcium carbonate deposits. In shoal waters and continental seas among terrigenous and carbonaceous sediments ferromanganese nodules and bauxites can be found. Their source is the colloidal solutions that are supplied by the rivers and that coagulate when fresh waters are mixed with those of the sea. In addition to this brown iron ores are formed in the coastal zone, while manganese sediments originate at some distance away from the shore in a more alkaline environment.

The formation of chemical sediments is not typical of the facies of continental slope. In the zone of ocean floor the main type of chemical sediments finds its expression in iron concretions. They represent rounded nodular emanations of colloidal clusters of hydroxides of manganese and iron, the concentric layers of which envelop minute meteoric particles, fragments of shells, and volcanic material. The size of concretions varies from several millimetres to 15-20 cm and more in diameter. The content of manganese fluctuates from 8 to 50%, that of iron is found to be between 2.5 and 27%. Besides, the content includes up to 30 chemical elements (nickel, cobalt, vanadium, molybdenum, titanium and others). The assumed reserves of concretions on the surface of the World Ocean bed comprise 10^{12} t.

The Practical Value of Chemical Sediments. The activity of lakes and swamps is connected with the formation of metallic mineral resources, viz. iron, manganese, aluminium, chemical and agricultural raw materials (rock salt, borates and soda), natural building materials: e. g. limestones, chalk, and dolomites. In sea basins there emerge deposits of iron, manganese, aluminium, limestones, and dolomites.

Biogenic (Organogenic) and Biochemical Sediments

The formation of biogenic sediments takes place as a result of the active life of organisms either at the time of their extinction, or in their interaction with the environment. Among biogenic sediments, mineral varieties as well as the organogenic proper ones are distinguished. The accumulation of sediments occurs predominantly in the aqueous medium.

Some organisms have the property to concentrate considerable quantities of chemical elements. Thus, in siliceous sponges the content of silica is 600 000 times greater than in sea water; in sea grass the content of iron is 2 000 times greater, and that of iodine in sea weeds is 1 200 000 times higher than in water. Besides, in organisms there can also be the accumulation of such rare elements as germanium, beryllium, cobalt, scandium, and molybdenum.

No minor role in the sedimentation of mineral particles that are various in their composition is played by bacteria. They take an active part in the processes of chemical weathering, thus giving rise to the inception of new biochemical sediments, as well as in the processes involving the precipitation of mineral salts

from the solutions, changing the chemical composition of the aqueous medium as a result of their life activity.

The Organogenic Sediments of Lakes and Swamps. The principal source material that forms these sediments consists of lower plants and algae, which enter into the composition of plankton. In the composition of algae the main function is with protein and fats, while the quantity of carbon dioxide in them is insignificant. On their extinction algae fall to the bottom, where in the practically complete absence of oxygen and under the influence of anaerobic bacteria, their remains are disintegrated with the result that there appears the so-called organic silt. This liquid colloidal mass with a pungent smell of hydrogen sulphide has been called *sapropel.* As the mass becomes more accumulated the semiliquid sapropel acquires a more compact form and is transformed into a brown and black consolidated, though very light mass, which is now characterized by conchoidal fracture, which is known under the term of *saprocol.* Sapropels and saprocols are of great practical use as a raw material for the production of Ichthyol and other organic compounds by means of dry distillation while recently it has been used as a valuable organic fertilizer.

In the composition of higher plants, which function as the other source of organogenic sediments, protein and fats play a subsidiary role, while the main importance is shared by carbohydrates. In the upper layers of water basin and when the supply of air is limited, there takes place a partial transformation of plant material into *mould,* or *humus.* In conditions of a total absence of oxygen and within the medium characterized by the activity of anaerobic bacteria the decaying plant mass is transformed into peat. At the expense of the decomposition of spores and epidermis entering into the content of higher plants the so-called *liptobioliths* are formed. All these transformations lead to the change of a lake into a swamp (Fig. 88).

Organogenic mineral substances that are formed during the accumulation of hard skeletal parts of organisms on the floor of basins are not particularly characteristic of lacustrine and palustrine deposits. In the regions of humid climate they include coquina, while tripoli and diatomites (siliceous deposits) are correlated with them in the areas of moderately humid climate.

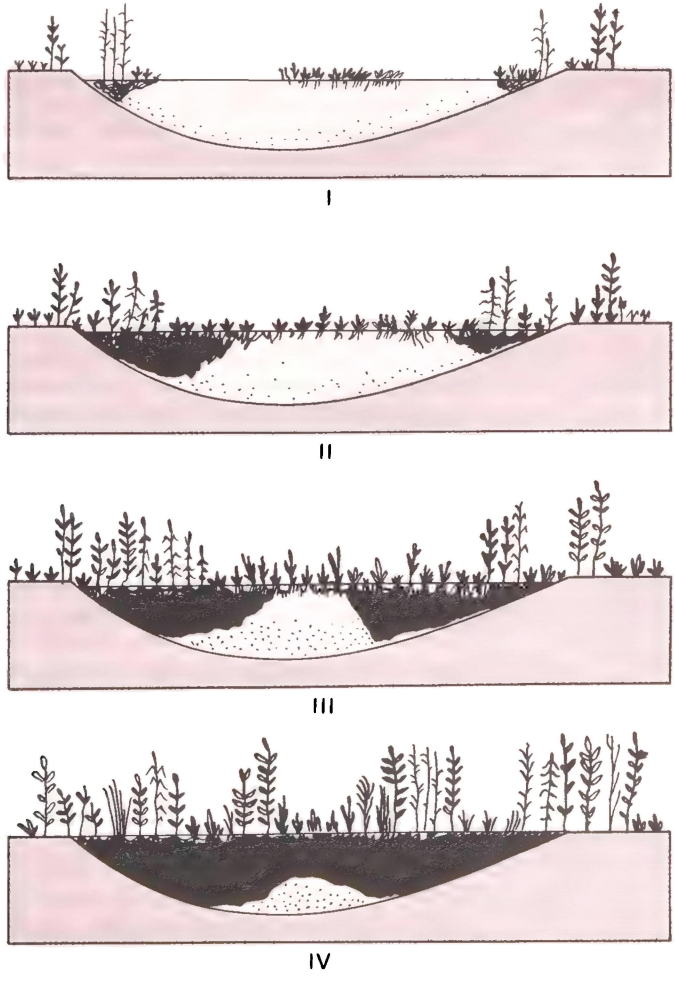
Organogenic Sediments of Seas and Oceans. The organogenic sediments proper are most characteristic of the shelf zone, though in some cases they can be accumulated in shallow water and even in the very proximity of the shore itself. On swamped sea coasts, particularly in subtropical regions, favourable conditions are created for the formation of peat. It is not infrequent that the accumulation of organogenic calcareous sediments occurs in the coastal region.

In the shelf zone organogenic sediments are mainly formed due to the dying off of various bottom-dwelling organisms, the skeleton of which consists of lime, silica, and to some minor degree of calcium phosphate. Calcareous organogenic sediments that are most widely spread are those that emerge at the expense of the concentrations of mollusks, corals, calcareous algae, and some of the simplest organisms. Particular interest is presented by corals, which in the process of their active life assimilate calcium from sea water so as to build highly stable constructions of various forms called *coral reefs.*

Biochemical processes in sea basins, within the shelf zone and in lagoons, can

become responsible for the formation of the deposits of native sulphur, which emerge at the expense of the decomposition of organic remains and sulphates of metals in the reducing medium by anaerobic bacteria. As a result of the activity of bacteria free pulverized or colloidal sulphur is precipitated down the floor of basins and saturates the mechanical and chemical sediments situated at the bottom. The depositions of sulphur are also formed during the dying off of anaerobic bacteria, the bodies of which are saturated with sulphur, which has been assimilated from sea water. In those cases when biochemical processes are activated on a large scale there occurs the precipitation of vanadium and uranium from sea water.

FIGURE 88. The transformation of a lake into a swamp (stages I-IV)



The formation of some types of mineral resources, e.g. phosphorites, is associated with upwelling. This has been illustrated by the paleographic reconstruction of phosphorite-bearing basins of Precambrian and Phanerozoic periods, where most of the largest phosphorite deposits were formed within the confines of oceanic shelves that were washed by powerful upwellings. The circulation of ocean waters in the process of upwelling acted favourably on the evacuation of large masses of cold waters containing phosphorus, silica, nitrogen, and other biogenic components dissolved in them by oceanic deep waters.

The active process involving the removal of geochemically mobile phosphorus (phosphate ion PO_4^{3-}) promotes its concentration on the productive oceanic shelves as a result of the changes in salinity, temperature, the value of pH and Eh, the content of CO_2, and other physicochemical parameters of a water medium.

An important function in phosphate sedimentation is attributed to the biogenic factor, which finds its expression in the existing marine organisms and in phytoplankton, in particular, which are the consumers of the dissolved phosphorus and the regenerators of this element, especially in porous waters.

Upwelling encourages the formation of phosphites in the stages of sedimentogenesis, diagenesis, and the bottom rewashing of phosphate grains, oölites, concretions, phosphatized biogenic remains with the formation of phosphorite deposits in the troughs (depressions) of oceanic shelves at the time of transgressions and regressions.

Organogenic sediments of continental slope are mainly formed at the expense of the destruction of shelf and coastal biogenic deposits. Among them coral and foraminiferal silts are found in the equatorial zones of Indian and Pacific Oceans.

Among the organogenic sediments of the oceanic bed formed at the depth, exceeding 3 000 m, calcareous and siliceous deposits are distinguished. Calcareous silts represent accumulations of microscopic shells of the simplest organisms (globigerines and pteropods). They are spread down to the depth of 4 000 m. Below this level calcareous silts are not sedimented, since thin shells are dissolved at greater depths in water that is undersaturated with $CaCO_3$. This is where siliceous organogenic sediments are represented by diatomaceous and radiolarian silts (oozes), composed of the armours of diatoms (algae) and shells of radiolarians.

The Practical Value of Biochemogenic Sediments. Biogenic and biochemogenic sediments are connected with the deposits of many kinds of mineral resources. The greatest industrial importance is shared by the deposits of caustobioliths, e.g. peat, pyroschists, and fossil coals that are confined to lacustrine and palustrine deposits. Biochemical nature is found to be pertinent to marine deposits, enclosing the deposits of phosphorites, native sulphur, carbonaceous and siliceous rocks.

Chapter 15 Diagenesis. Sedimentary Rocks

As the sediments of new accommodations grow and under the influence of gravitational forces they begin to interact with each other, the porous waters and the medium of their aggregation. This results in that there occurs a gradual transformation of the substance of the primary sediment, and at the place of sedimentation there emerge new formations that remain stable in the course of physicochemical changes of their environment. These processes of the transformations of sediments are called *diagenesis* while the thus appearing new formations are referred to as *sedimentary rocks.*

Diagenesis

All the processes of diagenesis take place simultaneously, though the relative significance of each of them in the transformation of sedimentary rocks changes in time and is manifested with a different degree of intensity.

Immediately on the cessation of precipitation process, particularly in the aqueous medium, which accounts for more than 90% of sedimentary formations, the sediment becomes subjected to chemical and mineralogical alterations. No minor significance in the processes of *chemical transformation* of sediments is attributed to the processes of the dissolution of weakly stable minerals, e. g. halides and carbonates. The originally precipitated rock salts (halite, sylvite, carnallite, and others) can react with the residual brines that circulate above these sediments, becoming dissolved in them and precipitated again, which essentially leads to the creation of new mineral complexes. In addition to this, as a result of the flow of more fresh waters from the external sources some minerals are replaced by others, or the ones that remain more stable in the variable saliferous medium.

A considerable role in the chemical changes of primary sediments is played by different organisms, and chiefly by bacteria. Some of them decompose the organic substance, bringing about the emergence of carbon dioxide and hydrogen sulphide, thus altering the chemical properties of the sedimentation medium. Others are immediately involved with the redox reactions. For instance, aerobic bacteria convert the ferrous oxides into ferric oxides. Conversely, in the reducing medium anaerobic bacteria promote the regeneration of ferric oxides into iron sulphides.

Owing to the constantly varying activity of the sedimentation medium and the irregularity with which the new mineral species that emerge in the initial stages of diagenesis are distributed in it, there can later occur a redistribution of the substance of the primary sediment with the formation of concretions, or nodules, the composition of which is distinct from the sediment itself. The form and size of concretions are highly varied, which depends on the composition of primary sediment and the physicochemical conditions of the medium. It is not infrequent that concretions are formed as a result of the recurrent precipitation of the substance round some skeletal remains that function as the centre of the

concretion. The concretions that are most often found are the opal, chalcedony, phosphate, gypsum, ferromagnesian, and ferriferrous ones.

The process of diagenesis is characterized by dehydration, cementation, and consolidation of sediments.

The dehydration of a sediment takes place as a result of the squeezing out of porous water from the lower layer under the weight of overlying sediments. At the same time, there also occurs the process of dehydration of minerals that are rich in water, their recrystallization, and the extraction of readily soluble components from the sediment.

Cementation manifests itself in the filling of the porous space with the substance that binds together separate components of the sediment. The precipitation of the cementing substance can occur simultaneously with the formation of the sediment itself or in the subsequent stages of its transformation. In most cases the function of cement is performed by silicon in various modifications (quartz, opal, and chalcedony), oxides of iron, carbonates, phosphates, and others.

Consolidation, or the reduction in volume of primary sediments, is mainly conditioned by the pressure exerted by overlying sediments and takes place as a result of recrystallization, dehydration, and cementation of the sedimentary substance. Recrystallization exercises its influence chiefly on heterogeneous fine-grained sediments, consisting of easily soluble compounds. For instance, in the course of the diagenesis of reef calcareous formations, and under the influence of carbon dioxide, calcium carbonate is often transformed into a solution, and when the physicochemical conditions change, it is precipitated anew, though now in a crystalline form.

The character of transformation during the process of consolidation largely depends on the composition of primary sediment, mineral content, form and dimensions of fragments, the quality of the sorting of materials in the sediment, as well as on tectonic processes. For instance, quartz sand is cemented only without any noticeable change of the composition and size of particles, while in fine-fragmental carbonaceous silts recrystallization takes place within a short period of time and results in the formation of large crystals of calcite.

As a result of consolidation the physical parameters of sediments undergo marked changes at the expense of a reduction in porosity. Thus, after the sedimentation of some properly sorted coarse-grained alluvial sands, their porosity comprises from 40 to 60%, while in silts containing a large amount of finely-dispersed organic substance, it can be as high as 90%. With the increase of the load pressure of overlying sediments and the redistribution of grains the porosity of sands can go down to 25-30%, while that of the clays formed from silt substance can be within the limits of 30-35%. Under the normal conditions the process of consolidation takes place by means of a closer junction of fragments. Under the action of pressure of overlying masses and tectonic movements, fragments of minerals within the sediment begin to slide upon each other, split and become fissured at the points of their contiguity, which leads to a more compact packing.

In the long run all the processes that are being accomplished at the time of diagenesis result in that their sediments lose their friable and plastic qualities and

are transformed into *a solid petrified rock.* Migrating sands are transformed into sandstones, terrigenous silts into clays, bittern salt into rock salt, humic acids into peat, the fragments of carbonaceous shells and carbonaceous silts into limestones, etc. The rate at which the process of diagenesis takes place is highly varied and depends on the intensity of the accumulation of sediments, their composition, and the change of physicochemical and thermodynamic conditions of the sedimentation medium.

The significance of processes relevant to diagenesis is exceptionally great in the creation of sedimentary rocks and the layered sedimentary mantle of the earth's crust. Owing to the recrystallization of sedimentary substance in the process of diagenesis there occurs a concentration of mineral resources with the emergence of the deposits of iron, manganese, aluminium, sulphur, phosphorites, coals, etc.

Sedimentary Rocks

The Classification of Sedimentary Rocks. All sedimentary rocks are classified into four genetic types, viz., *fragmental, clay, chemical and biogenic*, and *pyroclastic varieties.* According to the material composition and characteristic features of sedimentation some subgroups are distinguished within each of these types.

Detrital rocks represent products of the mechanical disintegration of primary rocks. In accordance with the size and form of fragments the following subtypes are singled out among the detrital sedimentary rocks. They are: *the psephitic rocks* (boulders, pebbles, and gravels) and their cemented varieties – *psephites* which consist of fragments that are from 2 to 200 m and more in cross section (conglomerates, breccias, and gritstones); *medium detrital rocks* (sands) and their cemented varieties – *psammites* with the diameter of particles ranging from 2 to 0.05 mm (sandstones); *fine detrital rocks* (aleurite sands and loesses), and their cemented varieties – *aleurites* consisting in the main of particles the diameter of which measures from 0.1 to 0.001 mm (aleurolites).

Clay rocks consist of products of mechanical and chemical disintegration of rocks. Clay sedimentary rocks are distinguished by the character of bonds that exist between the particles, plastic properties, mineral composition, and origin. According to the content of clayey particles that are < 0.005 mm clay rocks are subdivided into clays ($> 30\%$), loams (10-30%), and sandy loams (2-10%).

The terms 'loams' and 'sandy loams' are used only in reference to rocks of the Quaternary age. For the Pre-Quaternary clay rocks only the term 'clay' is used irrespective of the content of clay particles that are less than 20%. If the composition of clayey particles is from 10 to 3%, then this kind of rock, which corresponds to the loam of Quaternary age is usually called argillaceous sand.

What has a comprehensive propagation in nature is carbonate and clay rocks, which, in accordance with the content of clayey particles, are further divided into limestone (dolomite) of the clayey variety, marl, clay marl, and calcareous clay of the dolomite type.

The chemical and biogenic rocks are formed as a result of the precipitation of mineral salts from the solution as well as the active life of organisms, their subsequent dying off and accumulation. The chemical and organic rocks are

connected with each other by mutual transitions and are consequently united into a single group. According to their composition rocks of this group are subdivided into following subclasses: carbonate rocks (limestone, dolomite, marl, and chalk); siliceous rocks (diatomite, tripoli, and opoka); halide and sulphate rocks (rock salt, potash and magnesian salts, gypsum, and anhydrite); ferriferous rocks (brown iron ores, ferriferous laterites); aluminous rocks (bauxites); phosphate rocks (phosphorites); caustobioliths (sapropel, peat, brown coal, hard coal, hard bitumens, and combustible schists).

Pyroclastic rocks consist of sedimentary detrital material and the products of volcanic activity. In accordance with the content of sedimentary and volcanic material pyroclastic rocks are subdivided into tuffs (less than 10% of sedimentary material), tuffites (10-50%), and tufogenic rocks (more than 50%). Depending on the size and the degree of roundness of sedimentary and volcanogenic fragments tufogenic rocks are classified in practically the same way as the sedimentary ones.

The Composition of Sedimentary Rocks. The mineral composition of sedimentary rocks is distinguished by a considerable variety. Among the minerals of sedimentary rocks we single out *the relict ones*, or those that are inherited from parent rocks, and *the sedimentary rocks proper*, which were formed by means of chemical and biochemical sedimentation.

More often than others the relict minerals can be found to contain quartz, feldspars, micas, and amphiboles, though the presence of other minerals of initial rocks cannot possibly be excluded. Among the latter, particular interest is presented by magnetite, ilmenite, chromite, zircon, tourmaline, garnets, and others, which in certain circumstances form valuable concentrations in industry.

Among the sedimentary rocks proper the number of principal rock-forming minerals includes groups of carbonates (calcite, dolomite, siderite, malachite, and azurite), halide compounds (sylvite, carnallite, and halite), sulphates (gypsum, anhydrite, and barite), and silicates (opal, chalcedony, kaolinite, and hydromicas). Besides the principal rock-forming minerals, the composition of sedimentary rocks includes the minerals of the groups of oxides and hydroxides of aluminium, iron, and manganese (limonite, hematite, goethite, manganite, pyrolusite, boehmite, and hydrargillite), groups of phosphates (apatite and calcium phosphate), sulphides (pyrite, chalcosite, and others), and native elements (sulphur).

In rocks consisting to a great extent of fragmental material, minerals, those that are the newly-formed ones, often form cementing material that occupies the spaces between fragments and serves to cement them. Minerals of this group are found not only in the form of earthy aggregates, but also give rise to peculiar segregations, e. g. concretions, secretions, nodules, peas, as well as various sintered forms – crusts, coatings, and buds.

A certain amount of *organic remains* of animals and plants is present in a large number of sedimentary rocks. The remains of living organisms are called *zoogenes*. *Phytogenic remains* are those of plants, and the mixed type is referred to as *zoophytogenic*. According to their composition the remains are distinguished as either siliceous, carbonaceous, or phosphate, as well as the remains of unicellular algae and spores, higher plants of lignite and cellulose composition,

epidermis and the tars of higher plants. In some sedimentary rocks organic remains comprise the main mass of a rock (organogenic limestones, diatomites, and coal). In other sedimentary rocks (oceanic clays) they enter into their composition as accessory constituents.

Rock Sedimentary Texture. In sedimentary rocks the textural peculiarities are mainly determined by the conditions of formation. Thus, each genetic type has its own textural features.

The structures of detrital and clay rocks are distinguished in accordance with the size of fragments, the degree of their roundness, as well as the means of cementation and porosity.

What acquires essential textural importance is the transformation of loose sediments into a compact rock, or cementation. Cement is distinguished as either contemporaneous (syngenetic) with the mass of rock and that of the later variety (epigenetic). The former can be exemplified by the clayey material in sandstones, which, when the sediment is consolidated, binds the components. Epigenetic cementation takes place in the process of deposition of the material from the circulation of aqueous solutions in the voids.

The most common cements are silica, carbonates, and various iron oxides. Depending on the relation of cement to fragments several types of epigenetic cement are singled out. They are: accretion, when cement is grown in the form of crusts upon fragments; the mechanical filling of porous space; the contact variety, when cementation is found only in those places where there is a contiguity of fragments; the corrosion cement, which pertains to the chemical impact of cement on the fragments which are thus corroded; and the regenerative type, which is formed as a result of the development of grains at the expense of the cementing material (Fig. 89).

The textural characteristic features of clastic rocks also include their *porosity*, which can be of large, medium, small and fine varieties.

According to its origin porosity is distinguished as either primary (when it emerges during the formation of the rock itself, as is, for instance, the case with intergrained porosity), or secondary, when it appears in already formed rock (for instance, as a result of the leaching of readily soluble minerals).

The textures of chemical rocks has a crystalline and granular form, and depending on the size of mineral grains are divided into clearly granular (> 0.1 mm), fine-grained (0.1-0.01 mm), micrograined and cryptograined, or pelitomorphic (< 0.01 mm) varieties. Moreover some chemogenic sedimentary rocks are characterized by oölitic texture (for instance, by some limestones and brown iron ores). Its basic structural elements are oölites that emerged when around a mineral or fragment of a shell a series of concentric layers was deposited (Fig. 90).

The organogenic rock textures are distinguished by a relative quantity of organic sediments and inorganic substance of a rock and by the properties of these remains. In accordance with the origin of organic remains zoogenic and phytogenic textures are singled out.

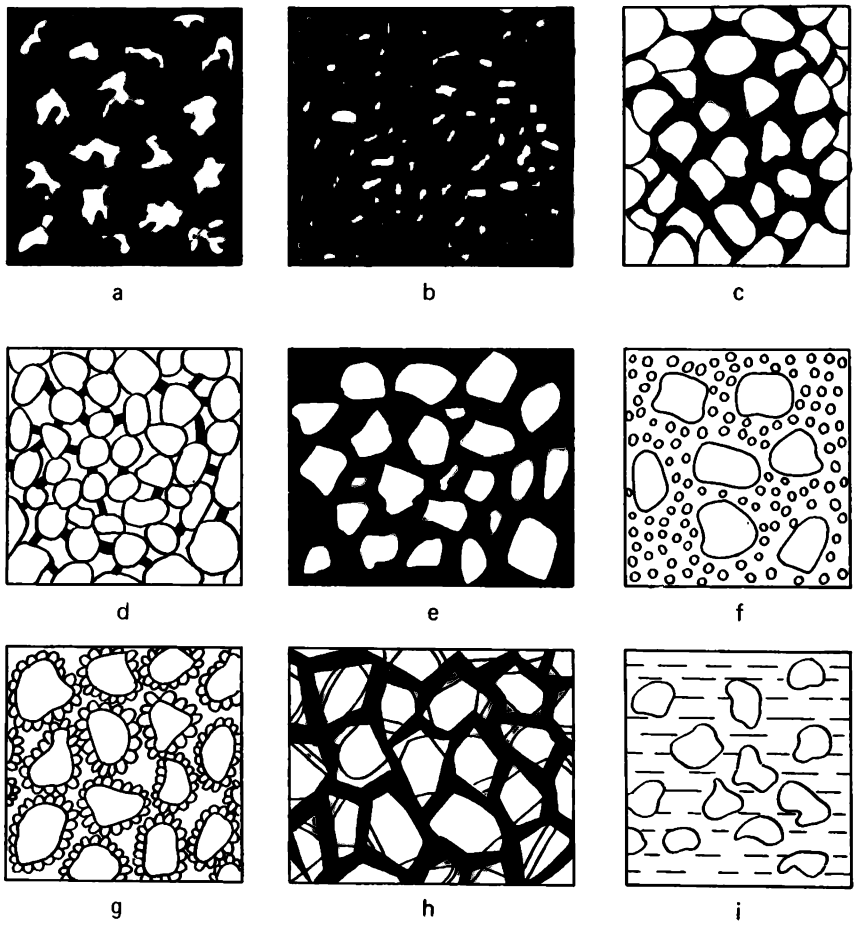
Structures of Sedimentary Rocks. One of the most typical features of sedimentary rocks is their composition, which characterizes the conditions of sedimentation and the change of these conditions in terms of time. As a rule, the composition of rocks has a layered form, which is expressed in the repeated

change of interlayers, that are distinguished from each other by granular and mineral content, the distribution of mineral constituents, colour, or some other features (Fig. 91). The more seldom the difference between interlayers manifests itself, the more perfect the lamination is. Besides the bedding for some sedimentary rocks massive (chemogenic rocks) and disordered (moraines, taluses, and downfalls) structures are typical.

Depending on the conditions relevant to the movement of sedimentation medium syngenetic lamination falls into two distinct types: the parallel variety, when the formation of sediments takes place in an undisturbed long-living

FIGURE 89. Types of cement (according to M. Shvetsov):

a - basal and corrosive type; *b* - basal and clotting (irregular) type; *c* – interstitial cement; *d* – contiguous (contact) type; *e* – interstitial and filling type; *f* – random granular and crystalline variety; *g* – overgrowing (incrustate) type; *h* – growth (regeneration) type; *i* – penetration



medium, and the cross-bedding, which emerges under the circumstances of the medium in motion. In addition to this, as a result of tectonic movements and gravitational processes, various types of bedding deformation are found in individual sedimentary rocks.

The cross-bedding is subdivided into several types with respect to angles of inclination of layers, their slope, the value and form of their components, entering into the composition of some of the layers, the thickness of deposits, the area of their propagation, etc. (Fig. 92). To a greater or lesser extent each of these types characterizes the conditions in which sedimentation occurs.

The horizontal or cross-bedding, formed within the process of sedimentation, can be disturbed by the subsequent geological processes, as a result of which sedimentary rocks acquire new structural characteristics. The deformations of bedding that are most widely spread are the ones that are under the influence of tectonic processes. There are also deformations that have emerged in the course of slumping and downfall phenomena; consolidation and recrystallization, dehydration, hydration, and the growth of concretions in the diagenesis of sediments, and others. Irrespective of the means of formation these exogenic deformations presumably take place even then when the rocks are in a state of plastic water saturation.

In bedded sedimentary rocks it is not infrequent that we can find sheet jointing, which finds its expression in the splitting of a rock into separate plates. In rocks without bedding (limestones and sandstones) the forms of jointing are very much the same as those of magmatic intrusive rocks, i. e. parallelepipedal, polyhedral, and spherical (in sandstones).

FIGURE 90. Structures of chemically sedimented rocks:
those of anhydrite (*a*), granular gypsum (*b*), oölitic limestones

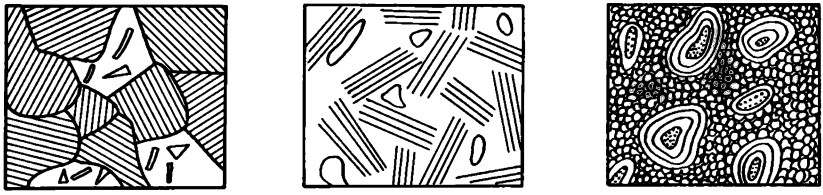
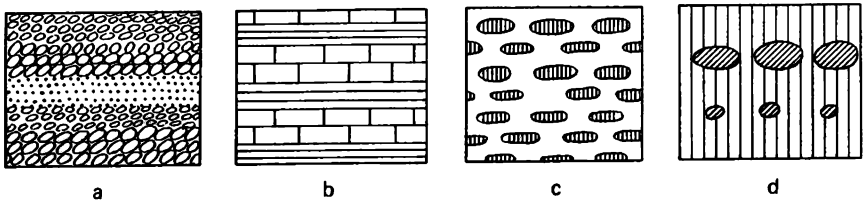


FIGURE 91. Parallel lamination of sedimentary rocks conditioned by:
change in the coarseness of grains (*a*); alternation of layers of different composition (*b*); horizontal orientation of particles (*c*); the arrangement of some material (concretions, boulders, shell fragments, etc.) in one plane



No minor significance in the study of sedimentary rocks is attributed to structural characteristics of their surface, which emerge in the interaction of the sediment that has been formed with the environment. They include the so-called marks of ripples, desiccation fissures, traces of rain drops, hail, and the movement of animals.

The Forms of Occurrence of Sedimentary Rocks. In most cases sedimentary rocks are found in the earth's crust in the form of tabular bodies, e. g. beds, lenses,

FIGURE 92. Types of cross-bedding: (according to I. Alison and D. Palmer):
a – littoral and marine type; *b* – type characteristic of turbulent rivers and streams; *c* – the ordinary river type; *d* – eolian type

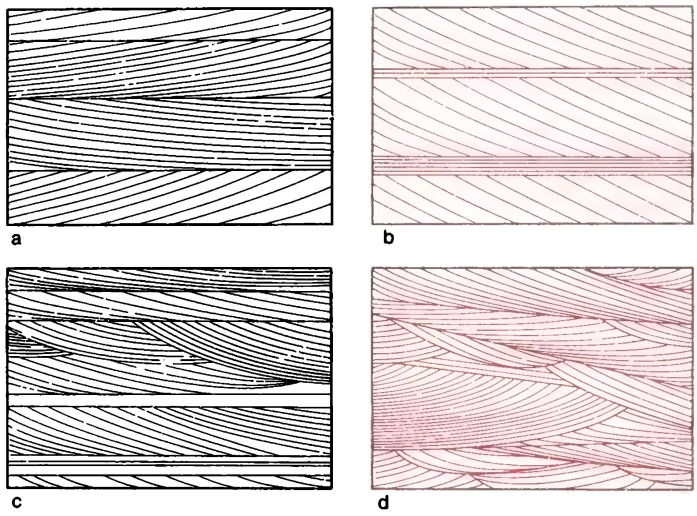
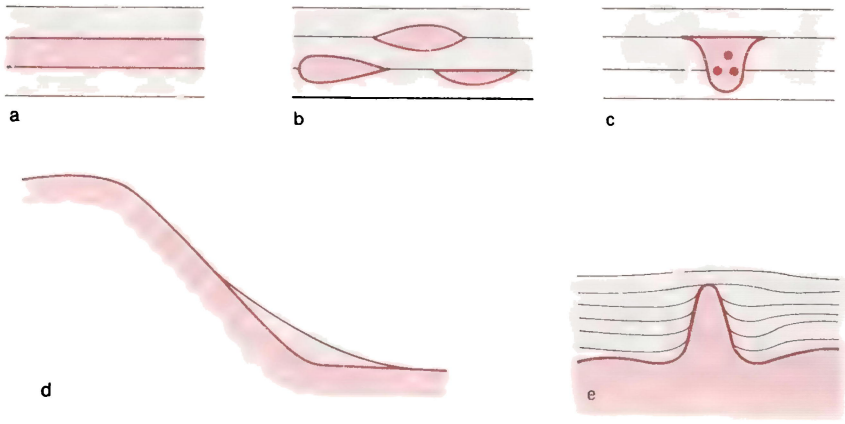


FIGURE 93. Forms of sedimentary rocks occurrence:
a – bed; *b* – lenticular deposits; *c* – pocket (nest); *d* – dome; *e* – sheath



and deposits, though they can also give rise to bodies of a more complex form of the type of nests or pockets, dome-shaped and stock-like deposits, and others (Fig. 93).

The forms of primary bedding of sedimentary rocks depend on the conditions and time within which sedimentation processes take place. Thus, marine sedimentary rocks are chiefly characterized by bedded forms of occurrence, the thickness of which remains consistent over vast territories. The less consistent thickness of the beds with frequent pinches is more typical of continental deposits, as well as the irregular form of the deposit, distinguished by a rapid wedging at short distances.

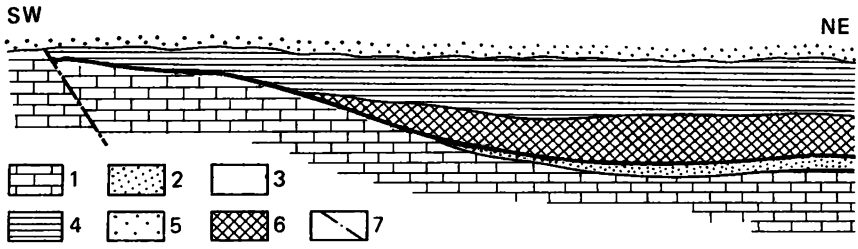
The Role of Sedimentation Processes in the Formation of the Deposits of Mineral Resources

In the process of sedimentation sedimentary deposits of mineral resources are formed at the bottom of basins. They are of enormous industrial significance. Among them we find deposits of building rocks (gravel, sand, clays, limestone, chalk, dolomite, marl, and tripoli), fossil salts, phosphorites, iron ores, manganese and aluminium, some nonferrous and rare metals, as well as all the deposits of combustible fossils (coal, combustible schists, oil, and combustible gas).

According to the place of their origin sedimentary deposits are divided into those that are either fluvial, palustrine, lacustrine, or marine, the latter being further subdivided into continental (platform) and geosynclinal types. In accordance with the character of sedimentation there are mechanical (fragmental), chemogenic (chemical), and biochemical sedimentary deposits.

The bodies of mineral resources have the form of beds, lenses, and are, as a rule, of large dimensions. They are bedded concordantly with the sedimentary rocks enclosing them; they usually occupy a particular stratigraphic position. The mineral composition of sedimentary deposits is remarkable for the presence of the fragmental minerals that remain stable under weathering, the products of chemical weathering, as well as sedimentary new formations.

FIGURE 94. The morphology of sedimentary ore deposits. Chiatura manganese deposits (according to A. Betekhtin):
1 – Upper Cretaceous limestones; *2* – subore quartz sands and sandstones; *3* – manganese horizon; *4* – schistose spongiolite rocks; *5* – Chokran sands; *6* – normal fault



Typical representatives of mechanical, or fragmental, sedimentary deposits of mineral resources are the deposits of gravel, sand, and clay. Among the gravel deposits the formations of temporary mountain streams, rivers, glaciers, as well as coastal, lacustrine, and marine deposits are singled out. Alluvial, lacustrine, and marine deposits are of greatest practical value among the sandy ones. Clay deposits are found in all the genetic classes of sedimentary formations.

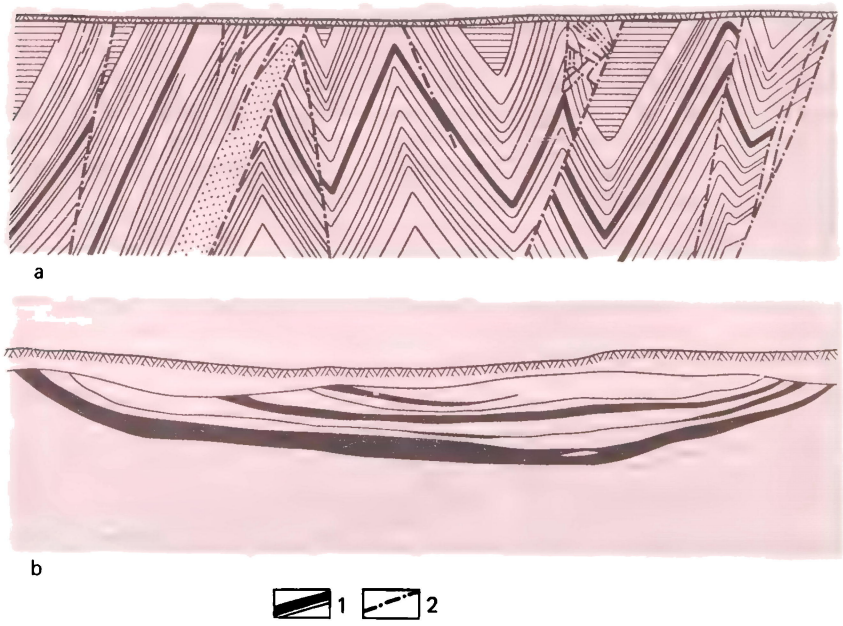
In the class of chemogenic deposits it is appropriate to distinguish from true solutions, which include mineral salts, gypsum, anhydrite, borates, barite, and deposits of iron ores, manganese, aluminium, some of the nonferrous and rare metals, that have emerged from the colloidal solutions.

Halogenic deposits of mineral salts are represented by natural brines and hard sediments of contemporary saline basins, saline underground waters, and fossil deposits. The largest deposits of fossil salts were formed in the terminal stages of the epochs of tectogenesis.

The deposits of iron ores, manganese, and aluminium were formed in similar geological conditions in river, lake, and sea basins. The most prominent of them are the marine deposits.

The class of biochemical sedimentary deposits includes platform and geosynclinal deposits of phosphorites, calcareous, siliceous rocks, as well as caustobioliths (Fig. 94).

FIGURE 95 Mode of occurrence and the morphology of coal deposits:
those of the geosynclinal type (*a*); those of the platform type (*b*); *1*–coal beds; *2*–tectonic deformation



All caustobioliths, viz. peat, combustible schists, brown and hard coal, oil and gas, are sedimentary formations of organic origin. They were formed within a wide range of geological conditions and in different geological periods. At the same time, it becomes possible to single out epochs of maximal accumulations of caustobioliths. The maximum of coal accumulations coincide with the Late Carboniferous and Early Permian periods (Donbass, Karaganda, Northern Kazakhstan), the Late Jurassic and the Early Cretaceous periods (Pechora, Tungus, Taimyr, and Kuznetsk basins), the Late Cretaceous and the Paleogene and Neogene periods (Lvov-Volynsk and Dnieper basins, Sakhalin). According to tectonic conditions the coal-bearing basins are divided into platform (near Moscow, Tungus, Kansk-Achinsk, and Irkutsk), transitory (Minusinsk, Ekibastus, Burein), and geosynclinal (Donesk, Kuznetsk, Karaganda, Pechora) varieties. In addition to this the coal-bearing basins of the groups that have been singled out are markedly distinguished by the thickness and number of coal beds, their extension and the degree of dislocation (Fig. 95).

On the whole, sedimentation processes are of extremely great importance in the formation of the deposits of mineral resources. They are connected with all the deposits of caustobioliths, the greater part of the reserves of widely spread building rocks, and the substantial resources of metallic ores and nonmetallic raw materials.

V Regularities in the Development and Structure of the Earth's Crust

With the complete abandoning of hypothesis, i.e. the trend of our thought, science would be no more than an agglomeration of bare facts.

K. TIMIRYAZEV

The substantial differences between the continental and oceanic types of crust, as has been mentioned in Chapter 2, show that the main structural elements of the earth's crust are continents and oceans. They are referred to the structural elements of the first order. In geophysical terms the boundaries between them lie not along the coastal line, but along the continental foot. In this respect continents comprise 2/5 of the earth's crust area, while the remaining 3/5 are accounted for by oceans. They are correlated with the basic stages of the crustal relief, divided by the differences in the altitudinal marks of about 5 km (see Fig. 6). The divergencies between the crust of continents and oceans are spread over to the upper mantle. Its considerable part under the continents enters into the lithosphere, the thickness of which is two to four times greater here than under the oceans.

Deep structures of the second order comprise mobile belts and stable blocks. On the continents they respectively include platform and geosynclinal (mountain-folded) regions, and oceanic platforms and mid-oceanic ridges within the confines of the oceans. The aforesaid structures enter into the composition of structural elements of the first order. In their turn they are divided into deep structures of the third order, the latter being subdivided into smaller regional and local structures.

According to the now prevailing concepts the lithosphere can be divided in its area into lithospheric plates in compliance with the geodynamic rather than structural principle. They should presumably be regarded as superordinal structures that are of greater size than continents and oceans.

Lithospheric plates are separated by seams, which correspond to all the main types of tectonic, as well as seismic and magmatic activity of the Earth. The boundaries between the lithospheric plates are traced by the distribution of the epicentres of earthquakes, which are concentrated in the narrow bands along the boundaries of the plates, and do not practically exist or are extremely rare over the vast areas within the plates themselves (see Fig. 48).

A small number (6-8) of large plates such as African, Antarctic, Pacific, and other varieties can be distinguished in modern structure of the lithosphere (see Fig. 104). These plates, excluding the Pacific one, comprise parts of oceans and continents. In addition to this minor plates (Arabian, Coconut, and others) are distinguished together with the contemporary orogenic belts (Cordillera, Mediterranean, etc.) consisting of microplates.

In what follows an attempt is made to present a consistent account of the characteristic features pertaining to the structure and development of oceans, which cover the greater part of the Earth's surface and continents, the tectonic regioning of the earth's crust on the whole and the territory of the USSR in particular, as well as contemporary geotectonic hypotheses. The ensuing section of the book ends with an outline of the research methods and graphical modelling of the crustal structure.

Chapter 16 Tectonic Structure and Development of Oceans

Structural Elements of the Oceanic Crust

The geological study of oceans was initiated at the end of the nineteenth century. Since the middle of the present century ample use was made of geophysical methods, modern technical means, and other facilities. It was only in the fifties and sixties that a sufficient amount of information had been obtained on the main features of the relief and structure of the ocean bed, the structure of the oceanic crust, the gravity field, the magnetic field of oceans, their seismicity and the heat flow. The research carried out by Soviet and American expeditions made a tangible contribution to these achievements. Over the period of 1968-1983 deep-water drilling was conducted from aboard the American rv 'Glomar Challenger' in which the Soviet scientists took part. More than 620 boreholes were made in all the oceans of the world with the exception of the central part of the Arctic Ocean.

As has already been mentioned (see Chapter 2), the oceanic crust is markedly different from the continental one in thickness (6-7 km) and composition (Fig. 96) (the lack of the granitic layer that is typical of continents). Within a considerable area the sedimentary layer of the oceanic crust measures several hundreds of metres. It has been established by means of deep-water drilling that the whole sedimentary cover of oceans has been formed over the past 160-180 mln years beginning with the Jurassic period. As far as its age is concerned the sedimentary cover of oceans differs from the continental one in that the development of the latter has covered one and a half billion years.

The second layer of the oceanic crust the whole thickness of which has been drilled in the Pacific Ocean and half of which has undergone drilling in the Atlantic Ocean, is composed of equal tholeiitic basalts. The lower part of the layer bears the traces of regional metamorphism with respect to low-temperature facies. The accumulation of basalts of the second layer has taken place very rapidly, the period covering not more than one million years.

According to the data furnished by dredging the third layer of the oceanic crust is composed of holocrystalline basic magmatic rocks (with the predominance of gabbro), as well as of serpentinous amphibolites, peridotites, and pyroxenites. It is assumed that these rocks enter into the composition of the lower part of the third layer as a peculiar banded complex, represented by the differentials of basaltic magma.

In the structure of the World Ocean floor the following structural elements are singled out: mid-oceanic ridges, oceanic platforms (plates), and peripheral zones of oceans (submarine continental margins) that are transitional with respect to continents.

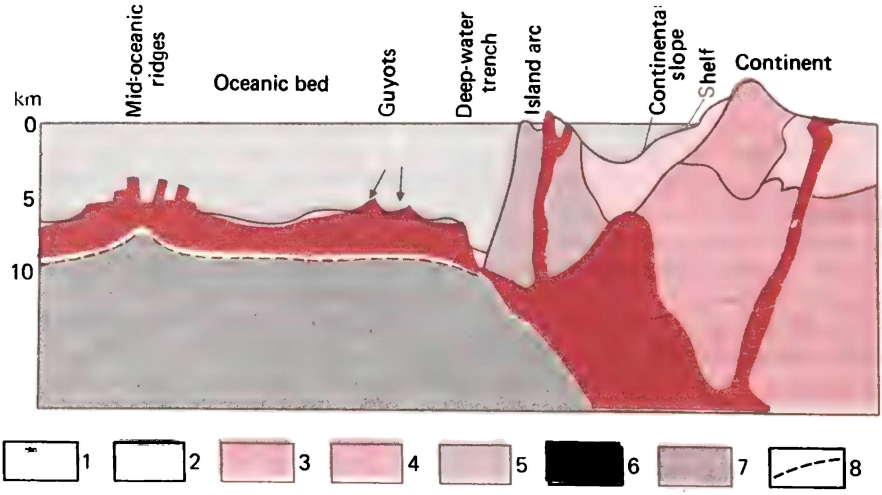
The mid-oceanic ridges have a planetary character of distribution and form a mobile belt the length of which is more than 60 000 km, with the width ranging from 0.5 to 2 000 km, and the height above the abyssal plains of up to 3-4 km. They occupy nearly one-third of the area of the ocean floor.

Not all the elements of the global system of mid-oceanic ridges conform to the general regularity, i. e. not all of them are medial, while some of them extend to the continents, and, hence, cannot possibly be regarded as oceanic (the Arabian and Indian and Eastern Pacific ridges). The median position, i. e. the one that is near to the meridian line, is characteristic of the ridges of the Arctic, Atlantic, and Indian Oceans (see Fig. 7). This is where they rise 3.5-4 km over the floor, with the width varying from 80 to 200 km. The South- and East-Pacific ridges of the Pacific Ocean are not strictly median in the proper sense of the term. They are situated in the southeastern part of the ocean, close to the Antarctic Continent and America. Their height does not exceed 1.0-1.5 km, and their width equals 2 500-3 000 km. Therefore, the ridges are but poorly distinguished in the ocean's relief.

Along the axes of ridges we find circuits of narrow and deep grabens, edged by mountain ranges and trenches with steep slopes. These are the so-called *rift zones*. They are clearly expressed in the median ridges of the Atlantic and the Indian Oceans. In the ridges of the Pacific Ocean they are either not found at all, or form an intermittent chain. It is not everywhere that axial zones of medial

FIGURE 96. A diagram showing the structure of ocean floor:

1 - ocean water; *2* – sedimentary layer; *3* – granitic massifs; *4* – granitic layer; *5* – the second oceanic layer (tholeiitic basalts); *6* – the third oceanic layer (gabbro and amphibolites); *7* – upper mantle; *8* – Mohorovičić discontinuity



ridges are expressed by rifts. In some parts of the territory they are represented by horsts (the East-Pacific elevation and the southeastern ridge of the Indian Ocean), which are confined to the zones of intense magmatic activity.

The mid-oceanic ridges are intersected with numerous transverse, or the so-called transform faults. They displace the axial rifts of median ridges in the horizontal direction over the first hundreds of kilometres. There are slips (opposite in sign) and unidirectional displacements taking place at a different rate.

The global (most prominent) transform faults intersect not only the median ridges, but also the adjacent oceanic plates and are even extended into the confines of the continents that enclose them. The length of such faults reaches several thousand kilometres, while the vertical displacements along them comprise up to 3-5 km. Within the walls of faults we can find natural sections of the oceanic crust, as well as the outcrops of rocks of the upper mantle.

In addition to the global transform faults, intersecting the whole area of oceans with the interval of up to one thousand kilometres, regional faults are distinguished that intersect the median ridge with the interval measuring the first hundreds of kilometres and the smaller faults dissecting the rift zones through every several scores of kilometres.

Median ridges consist mainly of magmatic rocks of the basic and ultrabasic composition (gabbro, diabases, peridotites, pyroxenites, and dunites) the metamorphism of which varies within a certain range. The thin sedimentary cover is increased in its thickness in the direction from the axial zones towards the foot. It is in exactly the same direction that the age of the deposits becomes greater in value. Almost everywhere the young basaltic lavas underlie the sedimentary covers.

The whole belt of mid-oceanic ridges is characterized by a high degree of seismicity with foci of earthquakes that are not too deep, which evidences the intense tectonic development of these formations. The measurements of the dynamic parameters of seismic foci show that tension may well be regarded to be predominant in rift zones. The axial zones of mid-oceanic ridges are characterized by a high degree of heat flow (7 times greater than its normal value). The seismic research has made it possible to establish that the mantle under the rift zones is bulged and disconsolidated within the confines of the band the width of which is 400-800 km.

Hence, the belt of mid-oceanic ridges is characterized by a manifestation of complicated endogenic processes. The emanation of a large quantity of energy in cases like these (as well as in geosynclines) results in various transformations that can be of the following types: mechanical transformations (fracturing of rocks, earthquakes, and shifts), thermal transformations (manifestation of volcanism, intrusions, and the enhanced heat flow), and physicochemical transformations (differentiation of magma, metamorphism, and hydrothermal processes). There is every reason to believe that within the confines of belts of mid-oceanic ridges the crust of oceanic type is formed.

In the opinion of scientists (G. Udintsev) rift zones have very much in common with geosynclinal regions. They are called *geoanticlines*. The study of banded magnetic anomalies, the measurements of the age and thicknesses of

sedimentary rocks across the strike of rifts substantiate the assumption concerning the extension of the lithosphere. This is precisely what makes it possible to attribute an exceptionally important role to mid-oceanic ridges in the formation of the young earth's crust.

Oceanic platforms, or *thalassocratons*, cover not less than 60% of the floor of oceans. The thickness of the earth's crust is found to be in conformity with the relief and fluctuates from 5 to 15 km. Thalassocratons are restricted by continental slopes and oceanic trenches on the one hand and mid-oceanic ridges on the other. Within these boundaries they consist of flat abyssal plains, divided by arched and block uplifts into isolated basins that have been called *thalaplenes* by G. Udintsev. Their relief is complicated by submarine hills and mountains (of up to 500 m) of volcanic origin. No traces of folding have been discovered within the confines of thalassocratons. The basic structures are represented by arched elevations, disjunctive dislocations, and the manifestation of volcanism.

The geological structure of oceanic platforms presupposes the participation of marine sediments of inconsiderable thickness, which are below replaced by more consolidated sedimentary rocks (clays, limestones, and diatomites) as well as volcanogenic formations. What lies at the bottom of oceanic platforms is a basaltic layer composed of serpentinous gabbro and peridotites. The age of the most ancient rocks does not exceed the Late Jurassic period.

Thalassocratons, as is the case with mid-oceanic ridges, are intersected by *a system of transform faults* (shifts) with the amplitude of displacement ranging from 150 to 185 km. In the relief of the floor they are expressed by ledges the height of which is up to 3 km, or series of horsts and grabens elongated along their strike.

Faults are found to be correlated with submarine volcanoes and volcanic islands, the number of which within the area of thalassocratons is very great. Among the sea-mounts of the thalassocratons of the Pacific Ocean there are many *guyots*, or isolated flat-topped sea-mounts of volcanic origin. Their flat peaks are submerged to a considerable depth from 300 to 2 300 m, which proves that the floor of oceans is in the state of subsidence.

The boundary between thalassocratons and the peripheral regions of oceans represents the basic seam structure of the Earth, along which the continental and oceanic types of the earth's crust are found to be contiguous. *The peripheral regions of oceans* include marginal seas, island arcs, and oceanic trenches. *Marginal seas* are markedly asymmetrical. From the side of the continent the subsidence of the floor is gradual; near the island arc the depth is found to be of maximum value. *Island arcs* are structures with yet unaccomplished folding, along which chains of acting volcanoes erupting andesitic lava are situated. *Oceanic trenches* are narrow (2-5 km) and deep (8-11 km) basins, connected with deep faults, gently pitching under the continent to the depth of up to 700 metres (the zones of Zavaritsky-Benioff). They serve as the structural boundary between continents and oceans where the replacement of the types of the earth's crust takes place.

The thickness and structure of the earth's crust is sufficiently homogeneous in peripheral regions that have not island arcs and consist of shelf and inland slope. The thickness of sedimentary rocks, not large on the shelf, sharply increases

under the inland slope. The sedimentary cover is underlied by the crust of continental type. In the ocean at inland foot slope it is replaced by oceanic crust. The earth's crust thickness decreases from 30 to 35 km on the shelf at a distance of 200 km approximately and up to 10-12 km behind the inland slope in the ocean. The sharpest crust thickness decrease takes place on an inland slope. The earth's crust is analogously built near the coasts where oceanic trenches occur but there are no inland arcs (South America).

Views on the Formation of the Tectonic Structures of Oceans

The problem concerning the origin of oceanic troughs, the age of oceans, and the history of their development is highly complicated and has not yet received any satisfactory solution due to the insufficient number of geologically tenable facts and the relative novelty of the scientific study of oceans itself.

Until recently a large number of geologists regarded continents and oceans as coetaneous formations. In their opinion, different stages in the development of the Earth within the process involving the differentiation of the substance constituting the mantle were in some cases characterized by the formation of the crust of continental type, while oceanic variety was typical of other instances. At the same time, the degassing of the mantle substance gave rise to the primary hydrosphere and atmosphere. The continents constructed by a relatively lighter sialic crust were found to be hypsometrically higher than oceanic troughs, and thus the latter were filled with water. Hence, continents and oceans were considered to be equally ancient, or *primary*, formations.

These views on the origin of oceans gained no further ground and were then reconsidered, as a result of which it turned out that the earth's crust of oceanic troughs was much younger than that of the continents. On this basis there emerged views of the *secondary origin of oceans.*

As far back as at the end of the nineteenth century the Austrian geologist E. Suess, having analyzed the available materials on geology, flora, fauna, and other characteristic features of southern continents, came to the conclusion that in the Paleozoic period there existed a southern supercontinent which united Australia, Antarctica, Hindustan, Africa, and South America. This land was called Gondwana (after the name of Gond culture group in India). Still earlier sufficient evidence was supplied to prove that there had been a northern supercontinent Lavrasia, which included Europe, Asia, and North America. However, if the separation of Asia from North America by the Bering Strait took place within a relatively recent period of time as a result of the post-glacial transgression of the sea, then there is some reason to believe that the southern continents had been disjoined much earlier.

The age of the Atlantic, Indian, and Arctic Oceans is approximately dated as Post-Late Paleozoic, if we take into account the fact that all the folded systems ranging from Proterozoic to Late Paleozoic ones are truncated across the strike by the coastal lines of these oceans. At the same time, the Pacific Ocean basin is fringed with folded belts, the age of which increases from the Alpine to that of Proterozoic as the distance from the shore becomes greater. Hence, the Pacific

Ocean is regarded by some scientists as ancient and primary, while others consider it to be newly formed though older (Proterozoic) than the other oceans.

The question that inevitably arises concerns the mechanism that lies behind the formation of ocean and its basic structures. V. Beloussov has elaborated a concept of directed transformation of the earth's crust of continental type into the one of oceanic variety. According to the hypothesis the whole of the earth's crust was initially of continental type. Until the end of the Paleozoic era there were no oceans on Earth in the sense that is attributed to them now. At the end of the Paleozoic and the beginning of Mesozoic periods, as a result of a marked excitation of the asthenosphere and the fracturing of the continental lithosphere into numerous blocks, there took place the evacuation of mantle substance and powerful basaltic outflows. They were precisely what accounted for the basification of the continental crust and its transformation into the crust of the oceanic type.

According to V. Beloussov, in the Atlantic and the Indian Oceans the processes of basification have been developing from the marginal parts towards the centre, in the direction of the mid-oceanic rides, in which they take place even now. In the Pacific Ocean basification was directed from the centre to the periphery and was superimposed upon the young active geosynclines, in which at that time the granitic layer was being formed. These processes were exactly the factors that conditioned the complexity in the structure of the peripheral zones of the Pacific Ocean.

V. Beloussov's conclusions concerning the young age of the Pacific Ocean were substantiated by the results of the drilling operations that were performed from aboard rv 'Glomar Challenger', according to which the age of rocks lying on the basaltic layer is not older than Late Jurassic. Nowadays, however, comprehensive factual material has been collected, according to which the idea of the development of the earth's crust from the oceanic type towards the continental variety may well be regarded as adequately tenable. The sum and substance of these views, forming the basis of plate tectonics, is discussed below.

Chapter 17 Tectonic Development and Structure of Continents

In the course of geological development one can find a particular regularity with which certain processes conditioning the general heterogeneity in the structure of the earth's crust and specific features of its individual zones find their expression. The development of the earth's crust was not simultaneous in its different parts. Hence, some blocks of the earth's crust are at present in different stages of their development, and differ from each other by geological structure, the content of rock masses entering into their composition, as well as the character, orientation, and intensity of geological processes that take place within their limits.

Depending on the directivity of these processes within the confines of continents geosynclinal and platform regions are singled out. The analysis of the development and sructure of the earth's crust in the said regions is based on the

current theory of geosynclines, which proves to be a remarkable generalization of all the data on the geology of continents.

The scientific study of geosynclines originated more than one hundred years ago in connection with the research carried out by the American geologists J. Hall and J. Dana. In later years the geosynclinal theory was further developed and became a modern branch of science owing to the investigations carried out by M. Bertrand, G. Haug, H. Stille, K. Bogdanovich, A. Borisyak, A. Arkhangelsky, N. Shatsky, M. Muratov, A. Peive, V. Khain, Yu. Sheinman, Yu. Kosygin, and others.

The new stage in the development of the study of geosynclines goes back to the sixties and seventies of the present century and was made possible by the success that had been achieved in the geological research of the ocean floor. Views on the origin and factors conditioning the development of geosynclines have also been somewhat changed. In connection with the emergence of neomobilistic concepts (plate tectonics and others), largely contradictory ideas concerning the development of geosynclines under the influence of global processes of movement and the interaction of lithospheric plates have been most persistently put forward. However, irrespective of the change of genetic concepts most of the scientists consider geosynclinal regions to be the most important elements in the structure of the tectonosphere. Our knowledge of them is changing with the general progress of science. The scientific study of geosynclines is continuously augmented by the ever-increasing new content.

Geosynclines, Their Development and Structure

The Characteristic of Geosynclines.Geosynclines, as they are understood today, are vast, usually linearly elongated structures of great length (up to 10-20 thousand kilometres), restricted by deep faults and distinguished by a high degree of mobility and penetrability (i. e. the frequent intrusion of magma into the earth's crust), which are characterized by a great variety of tectonic movements as far as intensity and orientation are concerned.

As a result of differentiated movements (i. e. the movements of different sign and scale), there emerge in them relatively narrow and linearly elongated throughs and uplifts. The troughs become remarkable for the accumulation of many kilometre thick sediments and occurrence of matamorphism. In the early stages of the development of geosynclines, subsidences are found to be predominant. In the later stages active elevations and the formation of folded mountain structures dominate. After the transformation of a geosynclinal region and its part into a mountain-folded piece of land and the peneplanation (levelling) following it at the place of the region or the part corresponding to it there appears a continental platform; the geosynclinal regime becomes extinct.

The study of geosynclinal zones of various age has made it possible to establish their following basic properties:

great velocities, scale (amplitude), contrast of vertical movements of the earth's crust, their block and undulated character, during which the contiguous zones separated by faults move in the reciprocal direction;

intense manifestation of folded and fault tectonic deformations, the development of linear folding, thrusts, and overthrust sheets.

prominent manifestations of earthquakes, considerable (up to 15-25 km) thickness of sedimentary rocks, accumulated in troughs, a high degree of variability of their facies composition across the strike of geosynclines;

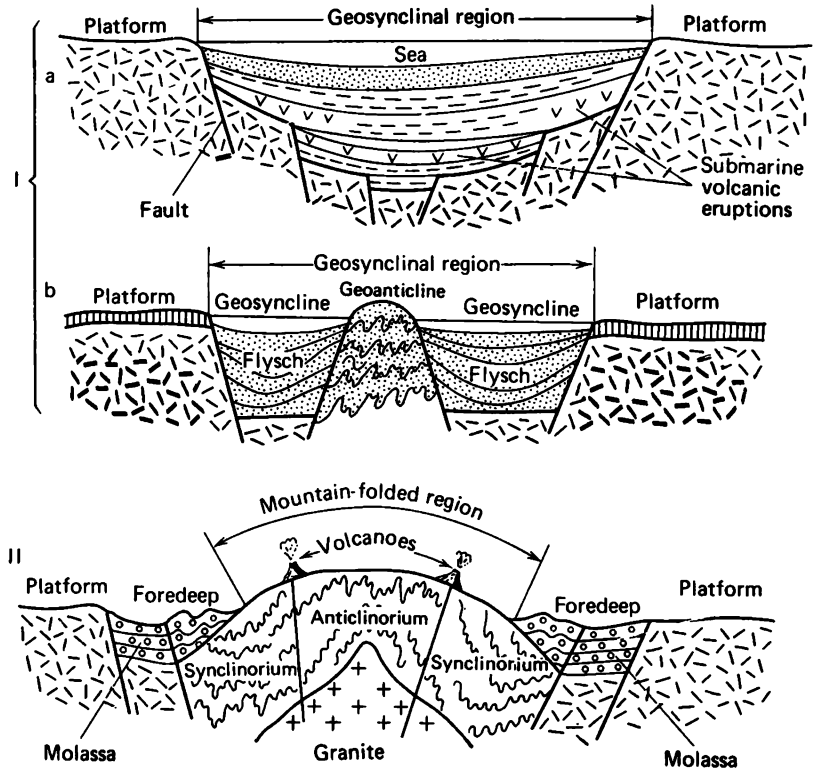
comprehensive development of processes pertinent to magmatism and metamorphism, and, consequently, of magmatic and metamorphic rocks;

enhanced geothermal gradient, which proves that heat flow becomes greater with depth.

Stages in the Development of Geosynclines. In accordance with the general outline given above, two stages in the development of geosynclines can be distinguished (Fig. 97).

The first stage (geosynclinal proper, or orthogeosynclinal) consists in that within certain parts of the territory there appear narrow (on the global scale) elongated zones that are called geosynclinal regions. They are characterized by a

FIGURE 97. A diagram illustrating the development of a geosynclinal region (according to V. Khain):
I – geosynclinal stage proper: *a* – the early geosynclinal stage; *b* – the late geosynclinal stage; II – orogenic stage



high degree of mobility of the earth's crust, excessive activity of all geological processes and are divided into the regions of troughs (intrageosynclines) and elevations (intrageoanticlines).

In the first stage of the development of geosynclinal region what warps most prominently is the central zone. This is followed by the warping that is spread in width, thus covering the marginal parts of the region as well. The troughs are penetrated by the seas, in which rocks of various composition are formed.

In deep troughs (measuring hundreds of metres) that are restricted by faults, with the participation of turbud streams and bottom currents there takes place an accumulation of sediments (or flysch) that are characteristic of this stage in the development of geosynclinal region, and that represent a seasoned fine alternation of sandstones, clays (argillites), and marls. In less deeper troughs that are usually situated in the marginal parts of the geosynclinal region, we find the accumulation of carbonaceous sediments.

Fractures give rise to magmatic processes and activise them. From the upper mantle, wherein fractures penetrate, there rise magmas of basic and ultrabasic composition. In troughs there take place submarine outflows, mainly of fissure type and the intrusions also take place.

In the zones where magmatism manifests itself with greater degree there emerge chains of volcanic mountains. As the development of the region progresses, the outflown lava of the basic composition becomes somewhat more acidic. We also find the accumulation of pyroclastic (volcanogenic and fragmental) rocks. The overall thickness of the sedimentary and volcanic masses, that emerge within this stage of the development of the earth's crust, often has several thousand metres.

The initial rate at which warping takes place is very high, but with the development of the geosynclinal region it becomes lower, though the area covered by warping is widened, which leads to the increase of transgression not only within the confines of the geosynclinal system itself, but also in the adjoining regions. In this stage the relief is rather low, and the relatively flat islands divide the sea troughs.

The most characteristic features of the initial phase (substage) of orthogeosynclinal stage are the following: general subsidence, accumulation of thick masses of sedimentary rocks, and the predominance of effusive magmatism over the intrusive variety. The duration of the said substage is particularly great, often covering more than a single geological era.

When a considerable mass of rocks (8-15 km) is accumulated in the troughs, the tendency towards the subsidence of the region is replaced by a gradual uplift. In cases like these the overall undulated oscillatory character pertinent to the movement of the earth's crust is retained. Uplifts originate first in the axial parts of central troughs; then they are spread sideways and cover the whole geosynclinal region, which warps, as it were, particularly in the central part. What takes place is the so-called inversion, or the transformation of the geosyncline into geoanticline.

It should be mentioned that, as was the case with the preceding substage of subsidence, the rate at which individual zones and blocks are elevated is extremely unstable in various parts of the geosynclinal region and can change in

the course of inversion. The different velocity of block movement proves to be conducive to the functioning of fractures along which the influx of magma continues. Effusive magmatism is gradually replaced by the intrusive variety. The composition of magma changes, and it becomes more acid.

In those troughs, where seas are preserved, accumulation is mainly related to fine-fragmental sediments, during the diagenesis of which we have the formation of clays and aleurolitic sandstones (in marine and lagoon conditions). Depending on the climate these deposits can be either carboniferous (humid climate) or saliferous (arid climate).

At the same time, with the uplifts there take place folded and ruptured deformations of rock masses. Folds of linear type are mainly formed, together with overthrusts, and processes of metamorphism and magmatism are manifested. In addition to this the ultrametamorphism and granitization of rocks evidence themselves at the lower levels of the basin.

The duration of this substage, as compared with the first one, is not great. Presumably it takes place not gradually, but within several periods called *phases of folding*, and which are separated from each other by intervals of relative calm.

The second, concluding stage of geosynclinal development is called *orogenic*. It begins with an overall elevation of the region, which, as a result of this process, becomes completely all land. The intense ascending movement involves the stable parts of the earth's crust that border the geosynclinal region. The movement of the earth's crust changes its character. The undulated and oscillatory movement becomes the one of block variety: separate and relatively hard lumps move along the comparatively vertical faults. In geology this type of movement has acquired the name of *block tectonics*.

In this stage effusive volcanism and seismic phenomena are activized anew. Magmatism acquires, in the main, the character of volcanism of the central type. The influence of deep faults is found to be in a chain arrangement of volcanoes and often in a synchronous resumption of eruptions. The composition of lavas undergoes changes too: they are represented by lavas of medium (andesitic) and acid composition (liparites, quarts-porphyries).

In the given stage of its development the geosynclinal region becomes transformed into a highland. The role of exogenic processes, particularly erosion, acquires greater significance in the course of elevation, while the river streams dissect and segment the uplifting region into mountain ridges. Landslide deformations of mountain slopes that are gigantic in their scope and that markedly complicate the conditions relevant to the occurrence of rocks participating in these deformations become most widely spread.

Denudation products of a mountain-folded structure are partially accumulated in intermontane depressions, though in the main, they are evacuated beyond the confines of the mountain-folded structure itself. In the depressions and troughs, predominantly in continental conditions, we have the accumulation of fragmental rocks, such as conglomerates, pebble-beds, interlayers of sandstones, sands, and sandy clays. The thickness of these deposits can reach 8-10 km and more.

Then, as the vertical movement slows down, mountain ridges become gradually lowered. The phenomena of denudation destroy the highland,

transforming it into a low-mountain relief, and lastly – into a hilly folded plain. In the long run the mountain-folded structure is cut down to its 'roots'. On the Earth's surface we find the outcrops of rock complexes that were formed in the deep zones of metamorphism (crystalline schists), ultrametamorphism (migmatites), and granitization.

Thus, as a result of the development of geosynclinal region there takes place the formation of thick sedimentary and volcanic masses, their folding and metamorphism. A whole complex of intrusions of igneous rocks ranging from the basic varieties to granites is emplaced into them.

Different stages in the development of a geosynclinal region are connected with the formation of magmatogenic deposits of mineral resources. The formation of the deposits of chromite, platinum, and titano-magnetite ores is found to be correlated with the basic and ultrabasic magmatic eruptions. Within the process involving the outflow of acid magmas of the inversion stage, complicated by regional and contact metamorphism, we have the formation of various skarn (contact and metasomatic), greisen and hydrothermal deposits of copper, tungsten, molybdenum, tin, antimony and mercury, gold, and uranium ores.

If from its very inception the development of the geosynclinal region has been taking place on the basis consisting of oceanic crust, the crust becomes substantially transformed as a result of this process. A fairly extended and thick complex of granitic and metamorphic rocks is formed. These rocks are precisely the ones that constitute the upper layer of the continents of the earth's crust. In other words, in the course of geosynclinal process there takes place the emergence of the continental earth's crust instead of the oceanic crust. If the geosynclinal systems of troughs were deposited on the continental earth's crust at the expense of breaking up and gaping of blocks of the granitic and metamorphic layer, then the thickening of this layer took place in the course of geosynclinal development. In individual parts of the earth's crust the geosynclinal development occurred two or three times, or, as is customary to say, had two or three cycles.

The geosynclinal regions are characterized by a complex (linear) type of folding, the development of intense deformations, the emergence of schistosity, flow cleavage, various forms of dynamic metamorphism, as well as deep faults and dislocations with a break in continuity (overthrust sheets and shifts).

The Structure of Geosynclinal Zones. The classification of geosynclinal structures presupposes their division into geosynclinal belts (structures of the largest size), regions and systems. Geosynclinal belts have the length measuring tens of thousands of kilometres, with the width of up to 2-3 thousand kilometres. They occupy the space between the stable plates of the lithosphere. The main geosynclinal belts comprise the Pacific, the Mediterranean, the North-Atlantic, the Ural-Okhotsk (Ural-Mongolian), and the Arctic varieties. All these belts have emerged in Late Precambrian. The three last ones completed their development at the end of the Paleozoic and the beginning of the Mesozoic periods. The Pacific and the Mediterranean belts partly continue their progress even in the present epoch.

Geosynclinal belts are subdivided into geosynclinal regions. They include

large segments (extending over 1 000 km) of geosynclinal belts, that are usually divided by the zones of transverse deep faults and are distinguished from each other by the characteristic features pertaining to their structure and development. Thus, the Ural-Okhotsk belt includes the Ural, Tien Shan, Central Kazakhstan, Altai-Sayan, and Mongol-Okhotsk regions. In its cross section each region consists of several geosynclinal systems and the median massifs that divide them. In the absence of median massifs the concepts of region and system are found to be interchangeable (e. g. the Ural region or system).

The geosynclinal system is a clear-cut linear structure covering the length from 1 to 3 thousand kilometres (the Urals and the Appalachians), the width of which varies from 200 to 600 km. The geosynclinal systems are situated either between the platform and the median massif, between two median massifs, or occupy the whole space between two platforms. In the contemporary structure of the earth's crust geosynclinal belts, regions and systems are respectively expressed by folded geosynclinal belts, regions and systems, since their sedimentary infilling had wholly undergone various deformations.

Median massifs represent stable and hard massifs of more ancient period of formation than the geosynclinal systems surrounding them. They have remained unaltered within the processes of subsequent folding. Within their confines the section of geosynclinal formations is either reduced or replaced by poorly dislocated platform formations. In the concluding stages of the development of geosynclines the median massifs are elevated in some parts, and subsided in others, thus forming uplifts or intermontane depressions.

The form of median massifs is usually angular and isometrical with the width measuring several hundreds of kilometres (up to 1 000 km). Large median massifs are distinguished by maximum stability and approach genuine platforms (Tarim and Indo-Sinai massifs). Smaller massifs (less than 100 km) are simply referred to as ancient blocks, situated among geosynclinal systems. The structures of geosynclinal systems are submitted to the contours of median massifs, thus fringing them. The contours of massifs themselves are determined by the boundary faults of geosynclinal systems. The same can be said of the relationship between the geosynclinal belts and platforms.

Median massifs are not monolithic, in the sense that individual geosynclinal troughs can be found within their confines. They are distinguished from the troughs of geosynclinal systems by a shorter period of their development, less prominent width and depth, and the variability of their extensions.

The basic structural elements of folded regions are the anticlinoria and the synclinoria, which are respectively grouped into *anticlinorium* and *synclinorium* zones. Large folded structures of anticlinal form within the folded region, consisting of anticlinoria and synclinoria, give rise to the formation of *meganticlinoria* (the Urals and the Great Caucasus); those of synclinal form become responsible for the emergence of megasynclinoria.

Within the confines of geosynclinal systems two quite different elements are distinguished: one for the internal zones called eugeosyncline ('adequately geosynclinal') and the other for the external zones known under the term of miogeosyncline ('inadequately geosynclinal'). The basic distinctions between miogeosynclines and eugeosynclines, besides the more external arrangement

upon the non-reworked continental crust, consist in the absence of any manifestations of initial, submarine basic volcanism and bodies of basic-ultrabasic holocrystalline rocks, i. e. of the magmatism of ophiolitic type, as well as in that miogeosynclines are involved in the folded and overthrust deformations later than eugeosynclines.

Miogeosynclines represent submarine peripheral parts of ancient platforms that are involved in geosynclinal subsidence. In geomorphological terms they are correlated with the regions of external shelf. What underlies miogeosynclines is a normal and poorly reworked continental crust. Eugeosynclines are mainly developed on the oceanic crust, while the fragments of more ancient continental crust that are retained in them undergo the process of profound reworking and take an active part in deformations.

The division into mio- and eugeosynclines finds a very clear-cut expression in the Urals (western slope – miogeosyncline; eastern slope – eugeosyncline), in the Appalachians, the North-American Cordilleras, and the Northern Andes. Essentially these examples refer to the marginal and continental strictly linear geosynclinal belts and to the zones of their conjugation to ancient platforms. In a number of systems eugeosynclinal zones are markedly reduced. They are found to be in correlation with only extremely narrow (several kilometres) ophiolitic seams with intermittent outcropping of the effusives of basic composition, basic and ultrabasic intrusive rocks. Ophiolitic seams of this kind are usually situated in the very back part of the geosynclinal system at the border with the median massif.

Epochs of Tectogenesis.The stages of intense tectonic development of the earth's crust, which find their accomplishment in the formation of the mountain-folded structures are called epochs of tectogenesis or epochs of folding. The latter, or tectogenesis, reflect the transition of certain blocks of the earth's crust from the geosynclinal regime to that of the platform type. They represent long periods of development estimated in tens of millions of years. As far as their quality and duration are concerned, they are in no way similar.

It is not infrequent that the epochs of folding follow each other without any marked interruption. Sometimes, even long before the end of one epoch of folding (at one place) it is followed by the next one (in some other part of the earth's crust). Thus, the intense tectonic development of the earth's crust represents, on the whole, a continuous process, though in some of its mobile parts the intervals between individual epochs of folding can reach millions, and even hundreds of millions of years.

In the history of the tectonic development of the earth's crust ten epochs of tectogenesis are distinguished. They are: the Saam, Belomor, Karelian, Satpur, Baikal, Caledonian, Hercynian, Cimmerian (Mesozoic), Alpine and Pacific varieties. Most of them are related to the Pre-Cambrian period, and only four coincide with the Phanerozoic period, which includes Paleozoic, Mesozoic, and Cenozoic eras.

The time and place of manifestation, as well as the main characteristic features of each of the Pre-Cambrian epochs of folding have not yet been given all the attention they deserve. Hence, their names for all the countries have not been established so far. Of the Pre-Cambrian epochs of folding the Baikal variety has

been studied more fully. It manifested itself in the Late Proterozoic (Riphean) period, and accomplished its development at the beginning of the Cambrian period.

The epochs of tectogenesis pertaining to the Phanerozoic period have been treated rather satisfactorily and have designations that are common to all countries. The Caledonian epoch found its expression in Cambrian, Ordovician, and Silurian periods and was accomplished at the beginning of the Devonian period. The Hercynian, or Late Paleozoic, epoch of folding was manifested in the Late Paleozoic and Devonian, Carboniferous and Permian periods (in places it began in the Ordovician period), with its completion falling on the Triassic period.

The Cimmerian, or Mesozoic, epoch of folding was expressed in the Mesozoic period (it began at some time in the end of the Paleozoic period) and had been completed by the beginning of the Late Cretaceous epoch. The Alpine, or Cenozoic, epoch of folding, started at the beginning of the Mesozoic period, manifested itself most prominently in the Cenozoic period, and has not reached its stage of accomplishment to this day. The Pacific epoch can also be referred to the Cenozoic age. It differs from the preceding epoch only in the zone of the main spread. The last two epochs are sometimes united into a single one known as the young Alpine epoch.

What is of particular significance is the fact that each epoch of tectogenesis begins with the deposition of deep geosynclinal troughs, in either geosynclinal belts that continue their existence, areas that have already undergone folding and reenter the geosynclinal stage of development, or the oceanic earth's crust.

Platforms (Their Development and Structure)

Characteristic Features of Platforms. The part of the earth's crust that has undergone the stage of geosynclinal development does not any more lend itself to warpings, elevations, and orogenic processes. It becomes, as it were, a hard monolithic block – a sort of platform, or craton.

The main characteristic feature of platforms is their two-stage structure. The lower structural stage, which is called basement, represents an eroded folded structure that appeared in preplatform (geosynclinal) stage of the development of the given region. It is composed of markedly dislocated and metamorphosed rocks with numerous dislocations with a break in continuity within them. The upper structural stage, called the platform mantle, is composed of gently deposited and almost non-dislocated sedimentary and effusive rocks. It was already formed in the platform period in the development of the given region.

According to the age of basement platforms are divided into those that are ancient and the younger ones. As has been suggested by N. Shatsky, it is customary to call platforms by the age of their basement with the prefix 'epi' attached to them. The ancient platforms include those the foundation of which was formed in the Pre-Cambrian period. Hence, ancient platforms are to be referred to as epiproterozoic. They constitute the cores of the present-day continents and are fringed by younger platforms and folded structures, or orogens. On the whole ancient platforms occupy approximately 40% of the area

of the said continents. They represent isometric, polygonal blocks of continental crust with the predominance of plain relief that is more than 1 000 km in cross section and the area measuring several million kilometres. The ancient platforms are separated from the contiguous young platforms by subvertical faults; while from the folded structures they are separated either by foredeeps, or by the overthrusts (overthrust sheets) along which these structures tectonically overlap the edge of platforms sometimes over the distance of more than 200 km.

Young platforms are deposited upon the Late Pre-Cambrian, Paleozoic, or Mesozoic folded foundation. In accordance with the age of foundation they are called: epi-Baikal, epi-Caledonian, epi-Hercynian, etc. The foundation of young platforms is characterized by a lesser degree of 'crystallinity' and isotropism than the foundation of ancient platforms; the rocks entering into its composition are less metamorphosed, contain fewer granites, and are distinguished from the sedimentary cover mainly in that their dislocation properties are more intense. Young platforms either fringe the ancient ones (Scythian and Turan), or fill the gaps between them (West Siberian platform). Their total area covers 5% of the continents. In the relief they are expressed by either plains of lowlands.

The platforms are characterized by the following common features:

relatively slow and poorly contrastive oscillatory movements of the earth's crust, with which the transgressions and regressions of the sea are connected;

relatively insignificant thickness of rocks of the sedimentary cover, usually not exceeding 2-4 km (in the regions of Leningrad and Moscow, approximately 200 m and 1 600 m respectively);

fairly equal composition of sedimentary rocks – carbonate and sandy-clayey marine sediments, continental red-coloured sandy-clayey, saliferous, and gypsum-bearing rocks;

horizontal, or almost horizontal attitude of the sedimentary mass, complicated by intermittent folding;

relatively weak manifestation of magmatism; effusive and intrusive magmatism had the expression only on some of the mobile platforms along deep faults, intersecting the foundation and the mantle (e. g. traps – fissure eruptions of basic and ultrabasic lavas, ultrabasic – alkaline intrusions);

the absence of any manifestations of regional metamorphism, relatively limited contact metamorphism manifestation;

low geothermal gradient.

Thus, platforms are characterized by intermittent folding and block displacements, which are correlated with vast arched uplifts and depressions. What is typical of platforms consists in that they have inherited the structures of both the foundation and the mantle.

Stages in the Development of Platforms. In the development of platforms five stages are distinguished in each tectonic cycle. The initial stage, or that of cratonization, is characterized by the preponderance of elevations and fairly intense intrusive (gabbro-anorthosites, granites-rapakivi), and effusive (acid) magmatism, which tends towards the periphery of platforms. The stage of cratonization is replaced by the early aulacogenic one, in which deep tectonic trenches filled with sedimentary masses are formed. In the end of the Pre-Cambrian period aulacogenes were transformed into troughs, and then into

syneclises (syneclisal stage), which, when merged with each other through anteclises, gave rise to plates with their continuous sedimentary cover.

The plate stage was the longest in the development of platforms and covered practically the whole of the Phanerozoic period on the ancient platforms. The cover, which was being accumulated during the plate stage is usually clearly divided into cyclically constructed complexes, corresponding to the principal tectonic cycles of geosynclinal belts. The plate stage was interrupted and completed by phases of tectonic and magmatic activization. The latter found its expression in the formation of rifts (late aulacogenes) and the origin of magmatic formations of the trap, alkaline and basaltic, as well as kimberlite varieties.

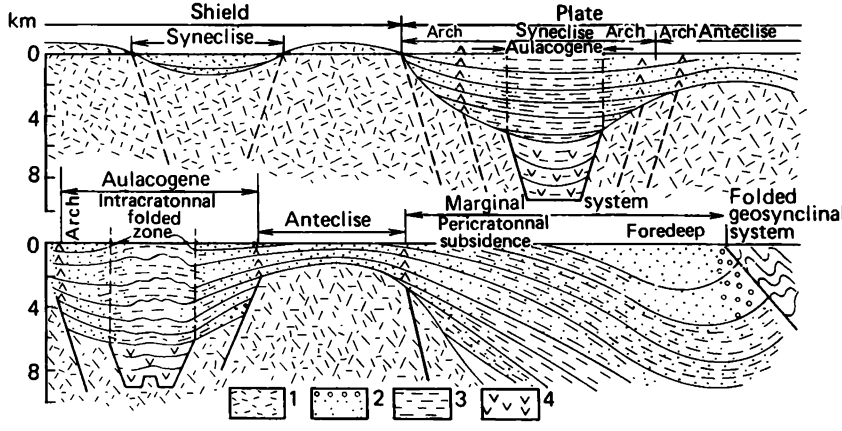
There is some reason to assume that the development of platforms is conditioned by external as well as internal factors. It is according to the external impacts, mainly the processes of extension, connected with the formation of contiguous geosynclines, that the contours and structural plan of platforms are determined. The intraplatform magmatism and the manifestations of intraplate tectonics are determined by the abyssal processes that take place in the deeper regions of the platform.

The Structure of Platform Regions. As has been mentioned before, the foundation of ancient platforms is mainly of the Early Pre-Cambrian period. The main role in its structure is shared by the blocks composed of Archean rocks. The latter are represented by greenstone belts, consisting of masses of volcanites and poorly metamorphosed sediments, as well as granite gneiss fields.

According to the position of the basement and the structure of sedimentary cover, structural elements of different orders are distinguished within the confines of platforms (Fig. 98). The basement of a platform come out onto the surface, approach it closely, or occur at a great depth. Correspondingly, the sedimentary cover can have various degrees of thickness or be absent altogether.

FIGURE 98. Main elements of the inner structure of a platform (according to V. Khain):

1–basement; *2-4*–sedimentary cover (*2*–fragmental deposits; *3*–clay and carbonate deposits; *4*–basic volcanites)



If the platforms themselves, as in the case of geosynclinal regions, refer to the structural elements of the second order, then the structures of the third order of the platform stage of development proper find their expression in shields, plates, and zones of pericratonic subsidences.

Shields represent large (of up to one thousand and more kilometres in cross section) areas of the exposure of platform basement onto the surface. They are typical of ancient platforms (Baltic, Ukrainian, and Aldan) and are seldom found on young platforms (Central Kazakhstan and Turan platforms). They are characterized by stable elevation and the prevalence of denudation over a greater fragment of their history. Less prominent exposures of the basement onto the surface are called massifs (e. g. the Anabar massif in the Siberian platform).

*Plates** are areas of continuous development of the sedimentary cover. They are most fully developed on the ancient platforms of the Northern Hemisphere. Young platforms are almost wholly plates (for instance, the Western Siberian and the Scythian ones).

Zones of pericratonic subsidences are areas characterized by the accumulation of coastal and shallow-water sea deposits with the thickness of up to 10-12 km. Their boundary with miogeosynclines is conditional and is drawn on the alteration of non-dislocated sediments by the dislocated ones.

Structural elements of the fourth order on the platforms include anteclises, syneclises, and aulacogenes. *Anteclises* are large, gently sloping uplifts within the confines of plates, which are overlapped by a thin sedimentary cover and which have an anticlinal form of the bend of the surface (e. g. Voronezh and Anabar varieties). In cases like these the basement is situated at the depth of not more than 1-1.5 km. *Syneclises* are large, gently sloping depressions, corresponding to the regions of the deep occurrence of the basement, that are filled with a thick mass of sedimentary rocks and have a synclinal form of the bending of surface (e. g. Moscow and Tungus types). Syneclises are characterized by large dimensions, isometric contours, and the gentle dip of limbs. The thickness of sedimentary cover in syneclises reaches 3-5 km, and the section is more complete than in the case of anteclises.

Narrow, extended (up to 200 km) and fairly deep tectonic trenches deposited over the deep faults are called *aulacogenes*. They represent large graben-troughs within the body of platforms, restricted by faults and filled with sediments of markedly enhanced degree of thickness (up to 10-12 km), and not infrequently also with volcanites of tholeiitic-basaltic or more often alkaline-basaltic condition. The mass of red sandstones, aleurolites and conglomerates composing the aulacogenes with carbonate and volcanogenic rocks are referred to the so-called molassic formation.

Anteclises and syneclises consist of structural elements of the fifth order; the former comprising *arches* (Tokmov, Tatar, Bashkir arches of the Volga-Ural anteclise), and the latter represented by *depressions*. A step lower in the structure of the sedimentary cover includes *swells*, i. e. linear zones of gently sloping elevations covering the length of the first hundreds of kilometres (up to 200-300

* In the English literature plates are called platforms, and craton is the term applied to ancient platforms.

km), with the width measuring scores of kilometres, and consist of one or several chains of local uplifts. The latter have the dimensions ranging from some to the first tens of kilometres, the height of the tens or the first hundreds of metres, and rounded (domes) or oval contours.

The interrelationship between platform and geosynclinal regions is usually expressed by three tectonic forms: marginal sutures, foredeeps, and less often – volcanic belts. The type of boundary structure depends on the characteristic features of the process involving the transformation of the geosynclinal zone into the folded region.

Marginal suture is situated on the border of the geosynclinal zone and the platform shield. It represents a narrow zone of deep faults. *Volcanic belts* are deposited in the marginal parts of the young platform and the geosyncline that is in the initial stage of its development and fringes it. Foredeep, or the marginal trough, as it is sometimes called, emerges when the subsided part of the platform becomes contiguous with the geosynclinal system. We know Alpine (Cis-carpathian, Ciscaucasian), Mesozoic (Verkhoyansk region), and Hercyan (Cis-Ural) marginal regions of epiplatform orogenesis and continental rifts.

For a long period of time geologists thought that mountain structures owed their origin directly to geosynclines and were formed as a result of folded deformations, completing their development. Nowadays it has been established that there is a possibility of a secondary involvement in the orogeny of the territories, which prior to this had for a long time been developing in the platform regime. It has also been suggested that formations of this kind should be called epiplatform orogens, while the name of processes of tectonic activization should be attributed to the processes owing to which the platform becomes transformed into a mountain-folded structure.

The secondary, or epiplatform orogens include mountain systems which emerged within the confines of the territories that for a long time prior to this period represented a platform. In the USSR these formations comprise the mountain structures of Tien Shan, Altai, Sayan, Baikal, and Transbaikal regions. They were formed in the Baikal, Caledonian, and Hercynian epochs of orogenesis, after which they were transformed into a young platform, but regenerated again beginning with the Oligocene period. The platform stage of the development is an evidence of the remnants of the sedimentary cover, which in the Tien Shan, for instance, can hardly be distinguished from the neighbouring Turan plate.

Epiplatform orogens consist of the alteration of mountain structures and intermontane troughs. The latter usually cover a smaller area and have oval contours. In some parts of the territory epiplatform orogens are separated from the troughs of the piedmont type (Chuya, Cis-Kunlun and other troughs). In cross section epiplatform mountain structures are characterized by an arched and block structure.

Intermontane and submontane areas are filled with thick, of up to 10 km and more, (Fergana, Afghan-Tadzhik troughs) molasses (soft, fine-grained calcareous sandstones), that are regularly transformed into the coarse-grained deposits as former move up the section. Mountain structures are often overthrust upon the intermontane troughs, while their molassic filling reveals the manifestation of folded deformations. Folds are mainly of the brachy-formed

type. Magmatic manifestations are widely spread, and the diapirism of saliferous deposits finds its most obvious expression. Granitoids, related to the deposits of polymetals, tungsten, tin, and fluorite, are found to be characteristic.

The regions of epiplatform orogenesis have a peculiar history of their development. Thus, the Northern Tien Shan, after Caledonian folding, and the Southern Tien Shan, after Hercynian folding, were actually transformed into a platform. In the end of the Paleozoic, within the whole Mesozoic, and the beginning of Paleogenic periods the Tien Shan had been developing as a typical platform: the mountains were eroded and in their place hilly plain was formed (of the Central Kazakhstan type). Since the end of the Paleogene, throughout Neogene and Quaternary periods, the young platform had undergone considerable activization. There appeared faults along which intense displacements of the blocks of the earth's crust of the arch and block character with the amplitude of 3-3.5 km took place. The amplitude and contrast of oscillatory tectonic movements became enhanced. The general amplitude of vertical movements comprised 9-10 km. Along the Talasso-Fergana fault intersecting the Tien Shan there occurred a displacement covering several kilometres. At the place of the platform there appeared a highland relief of the present-day Tien Shan. This process, judging by the high degree of seismicity, is going on even now. Practically the same can be said of the manifestation of tectonic and magmatic activity in Altai.

In connection with the unusual tectonic development of a large number of mountain-folded structures of the arch and block character they are included in a special group of *activated platforms*. The latter are regarded as highly important by many scientists. According to the data furnished by V. Khain, these regions cover 26% of the surface of continents and 90% of the area of mountain ranges of over 1 000-metre high. Thus, as far as their area is concerned, the epiplatform orogenic belts are at present found to be predominant as compared with the epigeosynclinal ones.

Continental rifts can be defined as extension structures, or the so-called gaping faults of a continental scale. Morphologically they are expressed by simple and complex grabens with a decreased thickness of the earth's crust and lithosphere with the protrusion of the asthenosphere upon the basement, enhanced heat flow, volcanic and seismic activity.

Continental rifts are characterized by great length (hundreds and thousands of kilometres) and markedly expressed linearity. Their width reaches scores of kilometres. Rifts (especially the large ones) correspond to the axial parts of the arched uplifts that have been developing for a long time, and in the contemporary relief are expressed by clear-cut depressions (rift valleys). Rifts are restricted by faults and strike-slip faults. Rift structures are found to be correlated with negative gravitational anomalies.

The development of rifts is accompanied by magmatism – ultrabasic-alkaline magmatism of the intrusive type, and that of alkaline-basaltic variety. Magmatites are connected with the deposits of cobalt, copper, nickel, chromium, and platinum (with hyperbasites); apatite, zirconium, aluminium, phlogopite (with nepheline syenites); tantalum, niobium, beryllium, and thorium (with alkaline granitoids and carbonatites).

Large continental riftogenic structures comprise rifts of the Baltic shield, aulacogenes in the foundation of the East-European platform, rifts of Hindustan, South Africa, North America, West Europe, the Baikal and East-African rift system, and the rift zone of the Red Sea.

Deep Faults and Ring Structures

As has already been pointed out, deep faults are characterized by planetary length, considerable depth of occurrence and the duration of their development. They separate the blocks of the earth's crust, which are distinguished by their structure, regime, and history of development. The length of deep faults is measured in hundreds and thousands of kilometres (the Main Ural fault is 2000 km long). The width of deep fault zones reaches scores of kilometres (the fault that has just been mentioned has the width of up to 20 km).

Deep faults are correlated with various forms of magmatism. They are discovered by means of geophysical methods (the gravimetric and seismic ones) as a result of abrupt changes of the physical properties of rocks.

According to the depth of penetration, deep faults are distinguished as either crustal, lithospheric, or mantle. *Crustal* faults reach Mohorovičić discontinuity. They emerge as a result of the reaction to the stresses that cover the whole mass of the earth's crust. *Lithospheric* faults, disrupting the structure of the whole lithosphere, and dying out in the asthenosphere, are presumably the most widely spread ones. *Mantle* super-deep faults are established according to the depth at which the foci of earthquakes are situated. They are arranged along the margins of continents or island arcs and have the form of seismofocal Wadati-Zavaritsky-Benioff zones, situated at the depth of 650-720 km.

With the kinematic features taken into consideration, faults are classified into deep faults, gaping faults, upthrow faults, overthrusts, and shear-faults, i. e. faults connected with extension, compression or displacement. In accordance with their geological position faults are divided into three groups. Those belonging to the first group determine the boundaries of lithospheric plates. Faults of the second order delimit small plates and microplates, and the ones pertaining to the third order divide blocks within the confines of continents.

Ring structures include geological formations and elements of tectonic structure, which have a clearly expressed oval and rounded form. They comprise active and extinct volcanoes; intrusive massifs; granite gneiss domes; diapir structures, and saline domes in particular. The rounded form is typical of a large number of depressions on the Earth's surface (the Caspian Sea region and Transylvania), and some other elements of the relief.

According to their origin structures can be of the following types: structures of magmatogenic origin (volcanogenic, volcanoplutonic, and plutonic varieties); metamorphogenic structures (granite gneiss domes); structures connected with diapirism of saline and clay masses, and ice; explosive structures; structures of shock (meteoritic) origin; arched uplifts and depressions, and structures of heterogeneous origin.

Meteoritic craters and astroblems represent large depressions and basins on the Earth's surface, formed by the activity of powerful shock waves of short

duration, which emerge during the fall of large cosmic bodies. They can be found on all the continents. Their total number is about 130; 40 of them are on the territory of Canada, and 25 in the USSR. The size in cross section varies from 25 to 100 km. Nearly 20 structures have the diameter exceeding 20 km. Seven of them are in the USSR, including the Popigai astroblem.

In aero- and space photographs we can discern ring structures with the diameter ranging from 6 to 500 km. They are presumably of volcanoplutonic origin. The largest structures (of more than 90 km) are probably correlated with their ancient varieties and are originated at considerable depths. In a large number of cases they often correspond to the areas related to the consolidated earth's crust (Transylvanian and Caspian regions), to the zones of the earth's crust that are penetrated by melted mantle masses.

Chapter 18 Tectonic Zonation of the World

The main aim of tectonic zonation consists in creating a structural model of the earth's crust, which could help to establish the composition, age, form, position in space and the interrelationships of large geological structures within the boundaries of the region under investigation, individual structural elements, or the whole world. The ultimate result of zonation finds its expression in tectonic maps, which represent the theoretical synthesis of all known geological and geophysical data and are compiled with the precision that meets practical demands.

The basis of tectonic zonation comprises the principles of vertical and lateral (areal) heterogeneity of the tectonosphere, as well as the principle of classifications, which is expressed by the hierarchic systematization of tectonic structures and elements which has been discussed above. The recommended scheme of tectonic zonation contains principles of distinguishing tectonic structures according to the age of final folding with the new mobilistic concepts of the evolution of the Earth's lithosphere, and takes into account the role of endogenic processes (riftogenesis, tectonic activization, and magmatism) in the formation and development of the continental and oceanic earth's crust.

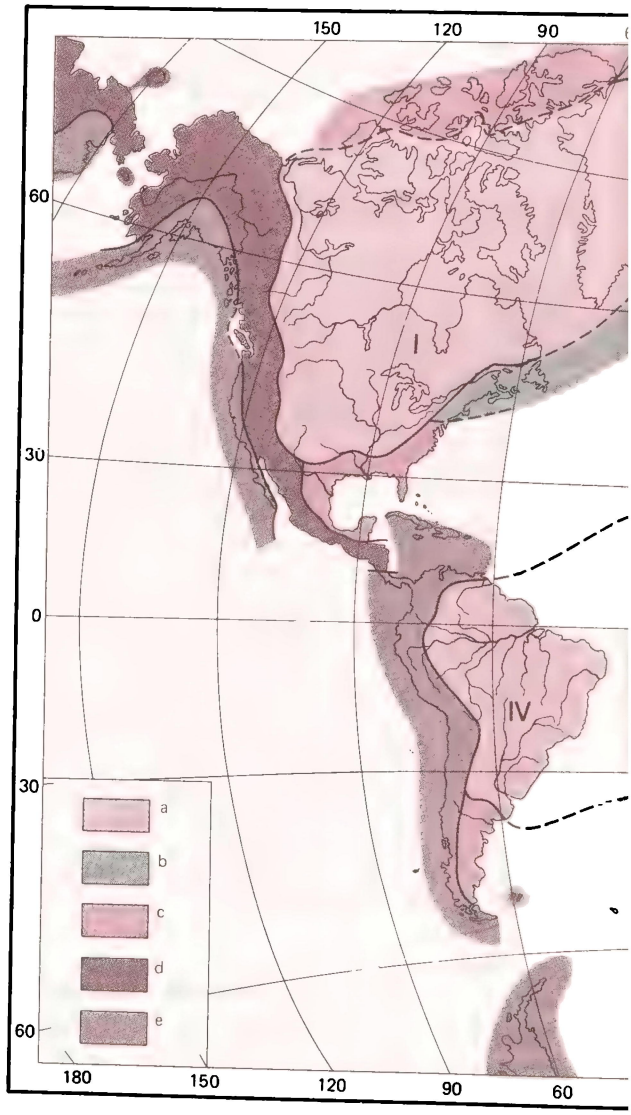
In the description of the tectonics of continents and oceans, individual regions and tectonic structures the following materials have been used: Explanatory Notes to Tectonic Map of the World – Scale 1 : 25 000 000 (V. Khain, L. Levin, 1980), as well as the Explanatory Notes to International Tectonic Map of Europe (N. Shatsky, A. Bogdanov, 1964), Tectonic Map of Eurasia (A. Yanshin, 1966), Tectonic Map of North America (F. King, G. Edmonstone, 1969), and other sources.

Tectonic Zonation of Continents

Within the confines of the earth's crust of continental type (Fig. 99) *ancient platforms* are distinguished. They have all the features of platforms and a two-stage structure, in particular. Their folded basement was formed in the

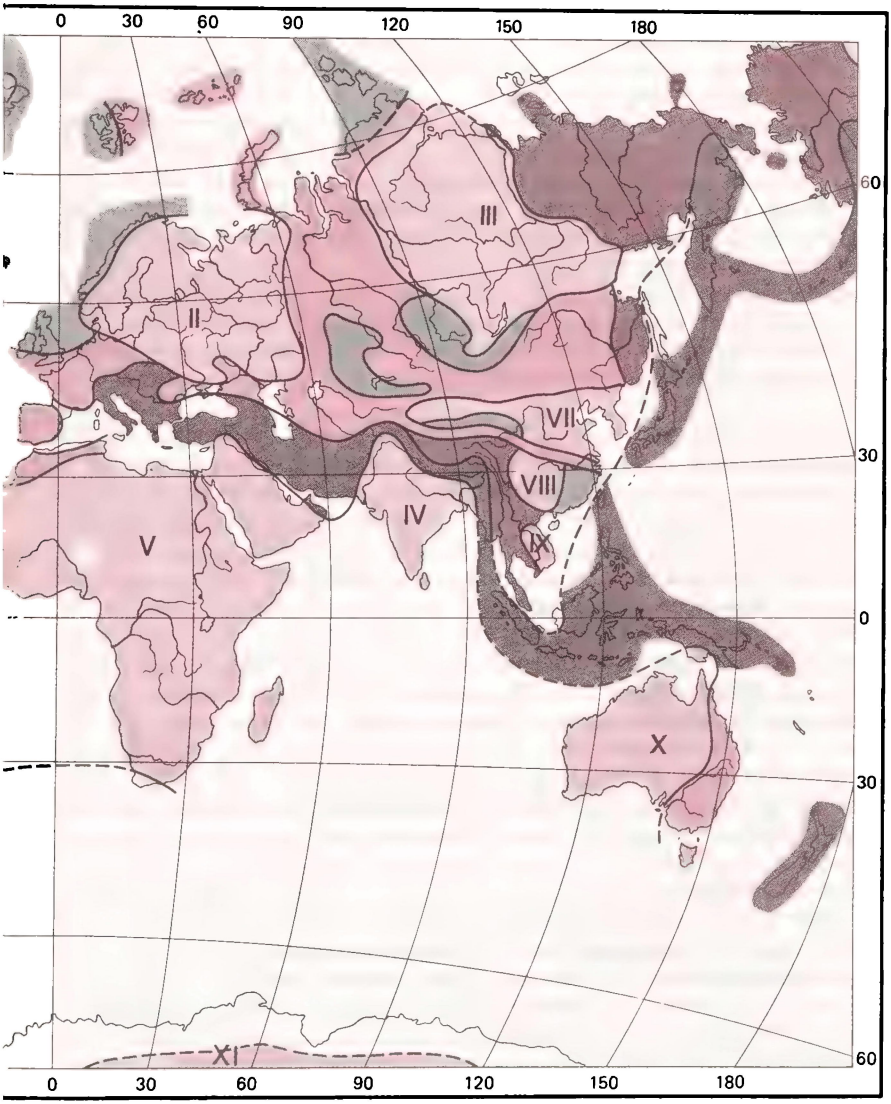
FIGURE 99. Tectonic zonation of the world:

a – Precambrian platform; *b* – Epicaledonian regions; *c* – Epihercynian platforms; *d* – regions of Mesozoic folding; *e* – geosynclinal ridges; *I* – Cordillerian folding; *II* – Verkhoyansk-Kolyma folding; *III* – Far-Eastern folding; *IV* – Indio-Chinese folding; *1* – coastal ridges; *2* Andean; *3* – Mediterranean; *4* – Ponto-Iranian; *5* – Himalayan; *6* – Indonesian; *7* – East-Asian



Paleozoic (Caledonian and Hecynian) epochs of techtogenesis, as a result of which young platforms were called epi-Hercynian or epi-Caledonian.

Together with them there are still younger folded regions, the geosynclinal development of which continued not only in the Paleozoic, but also during the whole Mesozoic period. These regions are essentially epi-Mesozoic platforms. However, within their boundaries and on top of the folded basement the new sedimentary cover had not had time to be formed. The relief of these regions, is,



as a rule, markedly dissected, and the folded complexes are almost exposed on the surface practically throughhout the whole area. Hence, with reference to the regions of Mesozoic folding the term 'platform' is avoided, though they actually represent the basement of the platform in the early stage of its existence. These regions are called Mesozoic mountain-folded structures, or mesozoids.

As is the case with mesozoids the places, where Paleozoic folded complexes are directly exposed on the surface, and the relief of the locality is fairly dissected, i. e. the areas which, by analogy with ancient platforms, should be called shields, are usually referred to as Caledonian and Hercynian mountain folded structures, or caledonides and hercynides.

The contemporary geosynclinal regions can be defined as mobile parts of the earth's crust, where mountain building processes are still in progress. In geomorphological respect they represent highland regions on the continents characterized by a marked contrast of relief, as well as mountain structures that develop from the sea and ocean floor in the form of island ridges. The contemporary geosynclinal regions are characterized by a high degree of intensity pertinent to the manifestation of all geological processes of endogenic as well as exogenic types.

Thus, continents consist of blocks that were formed in different epochs of tectogenesis and that occurred in different stages of their development. In their turn these blocks are constructed of still smaller positive and negative structural forms, which were developed as a result of the tectonic movements of the earth's crust.

Ancient Platforms (Cratons).They had found their expression in the continental earth's crust by the beginning of the Late Proterozoic period. Their folded basement consists of metamorphic rocks of the Archean and Early Proterozoic age (over 1.65 bln years). In the platform mantle there can be rocks of the Proterozoic, Paleozoic, Mesozoic, and Cenozoic periods. As a result of the differentiated movements of the basement the platform mantle on ancient platforms is represented only partially and not everywhere. The actual dimensions of platforms were considerably greater in the past. A certain part of their territory was found to be destroyed in the process involving the restoration of the geosynclinal regime in the subsequent epochs of tectogenesis.

In the Earth's structure ancient platforms form two basic series, viz. the northern and the sourthern ones. The northern, or Lavrasian, series includes North American, East European, and Siberian platforms, as well as the Chinese and Korean platform that adjoins them. The south, or Gondwana, series consists of South American, South Arabian, Hindustan, Australian, and Antarctic platforms.

The North American platform covers the great part of the continent bearing the same name. It is confined from all sides by younger folded structures. From north, east and south the platform is limited by caledonides and partly by hercynides from Canada, Greenland, Newfoundland, and the Appalachian Mountains; from west it is confined by thick Mesozoic folded system of the Cordilleras. A considerable part of the platform consists of the Canadian and Greenland shield divided by faults into several megablocks (the megablocks of the lakes Superior, Great Slave, Churchill, Great Bear, and others). With a

marked unconformity in relation to the megablocks there extends the youngest Pre-Cambrian mobile Grenville belt.

Between Rocky Mountains (a part of Cordillera geosyncline) and the western edge of the Canadian shield there extends the plate (pericratonic trough) of Great plains, which is composed of Paleozoic and Mesozoic deposits. The northern slope of the Canadian Shield also represents a pericratonic trough constituted by the formations of Lower and Middle Paleozoic periods. Within the confines of the platform there are syneclises (Michigan, Illinois, Forest City, Williston and other), anteclises (Cincinnati, Ozark Bend) and elevation (Transcontinental).

The East-European and Siberian platforms, which respecively cover the central and eastern parts of the Lavrasian series of platforms are treated at some length in Chapter 19.

The Chinese and Korean platform occupies an intermediate position between the northern and southern series of ancient platforms, though according to the character of its development it tends towards the northern series. Along the system of latitudinal faults from the north the platform borders with Paleozoic Ural-Mongol (Ural-Okhosk) geosynclinal folded belt, while from the southwest and south – with Nanshan and Quinglin Paleozoic systems. In the west the platform is contiguous with the epi-Baikal massif of Tarim-Alashan; in the east the platform adjoins the structures of the Pacific belt.

The basement of the platform comes out onto the surface, thus forming the Sino-Korean shield, as well as individual benches in the arch of the Shansi anteclise and in the Inter-Mongolian ridge. The negative structures of the platform are the North-Chinese, Phennam, Ordos, and Sun Liao syneclises.

The South-American platform covers the western part in the south series of ancient platforms. In the east it borders on the Atlantic Ocean; in the north, west and south it is contiguous with the Andes folded geosynclinal belt. The basement of this platform consists not only of the blocks of Early Pre-Cambrian continental crust, but also of the folded geosynclinal zones of Late Pre-Cambrian. The largest Early Pre-Cambrian blocks are the Guiana and West Brazilian shields, which are separated by the Amazon syneclise. In the eastern part of the platform there are Maranhão, San Francisco, and Paraná syneclises. In the west the platform is fringed by a continuous band of pericratonic depressions, separating it from the Andes. Along the coast of the Atlantic Ocean a band of perioceanic depressions is extended.

The African and Arabian platform is the largest in the Gondwana series of platforms. Within the greater part of its perimeter it is delimited by the Atlantic and Indian Oceans, and the basin of the Mediterranean Sea. In the other parts it is restricted by alpides, hercynides, and mesozoids. Within the boundaries of the platform there are blocks that had been consolidated by the Middle Pre-Cambrian (West-, Central-, and South-African varieties) and the Late Pre-Cambrian folded systems (Damar-Kibar and Arabian and Mozambique types). The northern part of the platform is covered by the Sahara plate, which comprises a number of elevations and syneclises.

In the southern half of Africa the sedimentary cover is filled with a chain of syneclises of Congo, Okovanggo, Kalahari, and Karroo, which are disjoined by the uplifts. The platform is edged with peripheral zones of subsidences, which are

turned towards the Atlantic and Indian Oceans, as well as the Mediterranean Sea.

The Hindustan platform has a triangular shape. In the southwest and southeast it borders on the Arabian and Bengal basins of the Indian Ocean; in the north it is confined by the folded system of the Himalayas, in the northwest it is contiguous with Beluchistan system, and in the northeast it adjoins the Indo-Burma system. Within the greater part of the platform the Archean basement comes out onto the surface. The Early Proterozoic age is characteristic of the Aravalli system in the northwestern part of the platform.

Within the boundaries of the platform the Vindhya and Kuddanakh syneclises are singled out. They are filled with Riphean Deposits. A considerable part of the platform (Deccan Plateau) is occupied by the exposures of trap magmatism. The northern parts of the Hindustan platform underwent activization on the border with the geosynclines that were transformed into folded mountain structures.

The Australian platform occupies the western and central parts of the Australian continent. The basement composed of the Early Pre-Cambrian formations covers practically half of the platform area. The Archean blocks are divided by the Early Proterozoic mobile zones. The following syneclises are distinguished within the platform: Canning, Joseph Bonaparte Gulf, Arafura, Ord, and others, complicated by graben-aulacogenes. In the sedimentary cover of the northern part of the platform there are manifestations of trap magmatism.

The Antarctic platform covers the eastern half of the continent. From the west it is restricted by the Trans-Antarctic folded system; the Atlantic and Indian Oceans limit the platform along the remaining part of the perimeter. The basement of the platform of Archean age is exposed in the seacoast. The Phanerozoic sedimentary cover in the exposed part of the platform has remained intact only within some small areas in the northwest of the platform. Other areas of the development of cover have been established by means of geophysical research in subice depressions of the Eastern Antarctic continent.

Folded Geosynclinal Belts.Within the limits of contemporary continents ancient platforms are divided by folded belts. They are composed of thick, complicatedly dislocated sedimentary and volcanogenic masses of the Upper Pre-Cambrian and Phanerozoic periods, which had undergone regional metamorphism and granitization. All geosynclinal belts that divide the ancient platforms were deposited in the Riphean period (1 400-850 mln years). The main geosynclinal belts are the North Atlantic (Atlantic), Ural-Mongol (Ural-Okhotsk), Mediterranean, Pacific, and Arctic varieties.

The North Atlantic folded geosynclinal belt separates the North American platform from the East European and African platforms, which, initially, as can be assumed, presented an integral whole. In the far northeast the belt consists of caledonides of Spitsbergen; their southern continuation is expressed by Scandinavian caledonides. The structure of Scandinavian caledonides is distinguished by great complexity and is represented by a series of subhorizontal tectonic sheets. On the other side of the North Atlantic we have the East Greenland caledonides, which, as is the case with Scandinavian caledonides, represent tectonic sheets. The British caledonides are at the same time correlated with the

continuation of the caledonides of Greenland and Scandinavian types.

The northern part of the Appalachian folded system represents Caledonian structures. The southern Appalachian Mountains (to the south of New York) are hercynides with a well expressed foredeep, filled with Upper Paleozoic deposits.

The Ural-Mongol folded geosynclinal belt is extended from the Arctic Ocean to the Sea of Okhotsk. It skirts the Siberian platform from the west and south, and separates in from the East European and Chinese and Korean platforms. In the west the composition of the belt includes the Hercynian folded systems of Novaya Zemlya and the Urals. The region of Paleozoic folding of Central Kazakhstan and the northern Tien Shan has a complicated structure and consists of large structural elements of the Caledonian and Hercynian epochs of tectogenesis. In the south there is the Hercynian folded system of the southern Tien Shan. In the east the Caledonian and Hercynian region of Central Kazakhstan borders along the large fault with the Late Hercynian Ob-Zaisan folded system.

Further to the east the Altai-Sayan folded region is situated. According to its structure it has very much in common with that of Central Kazakhstan. Within its boundaries to the west and south of the Siberian platform the ancient folded systems are replaced by the younger ones in the following order: baikalides-salairides-caledonides-hercynides.

The folded structures of the Baikal-Patom highland, Transbaikal region, North-Eastern Mongolia and the adjoining areas of China form as a whole the Baikal-Mongol-Okhotsk region. Its basic part is represented by hercynides. In the western part caledonides and more ancient formations can be found. In the eastern part the Hercynian basement is superimposed by the younger Mesozoic folding.

The Mediterranean folded geosynclinal belt extends itself from Gibraltar to Indonesia. The West-Mediterranean region includes the Alpine folded systems of the Pyrenees, Riff (North America), the Alps and the Pyrenees are characterized by a complex overlapped and markedly asymmetrical structure with the displacement of overthrust sheets over many scores of kilometres in the direction of foredeeps.

The East Mediterranean folded region consists of three systems: the Carpathian, the Balkan, and the Dinaric systems. The Carpathian Mountains continue the Alps, but are separated from them by basins. The largest of them is the Pannonia basin, which separates the Carpathians from the Dinaric Alps.

The Black Sea-Caspian region of the Alpine belt of Eurasia also consists of three folded systems: the Crimean-Caucasian-Kopet Dag system, the North Anatolia and Minor Caucasian system, and the Tavria-Zagros one. The transverse meridional faults separate the Black Sea and Caspian region from the Afghan-Pamir-Himalayan one. The Alpine folded systems, which comprise the last, form an enormous arc, which is directed northwards and skirts the northern protrusion of Hindustan platform. The central and the more steeply curved part of this are is correlated with the structures of the Pamirs and Penjab-Hazary, while its flanks correspond to the folded structures of Afghanistan and Beluchistan in the west, and the Himalayas and Transhimalayas in the east. These flanks are separated from the central part by the systems of shifts.

The Indonesian folded region occupies an intermediate position between the Mediterranean and Pacific belts. It comprises the Indo-Burma folded system, the Andaman-Nicobar inland arc and further the external Sunda arc in Indonesia.

The Pacific folded geosynclinal belt is the most enormous one of all geosynclinal belts of the Earth. Its formation had presumably begun with the end of the Early Proterozoic period and was connected with the development of the Pacific Ocean – the parental ocean of our planet with respect to which all the other oceans may well be regarded as its daughters. This belt is distinguished by a particularly high tectonic mobility and magmatic activity that existed almost continuously.

In the north-western part of the Pacific belt we have the Verkhoyansk-Kolyma system of Late Jurassic and Early Cretaceous tectogenesis. In the east it borders with the Koryak-Kamchatka system. They are separated by the Okhotsk-Chukotka volcano-plutonic belt. The southern protrusion of the Koryak-Kamchatka system is the Kuril Island arc, separated from the main aquatorium of the Pacific Ocean by a deep-water trench.

In the south the Kuril arc is connected with the Sakhalin-Hokkaido folded system, which is extended in the meridional direction. In the west there is the East Sikhote-Alin volcano-plutonic belt that separates the Sakhalin-Hokkaido system from the Sikhote-Alin folded system that is situated in the mainland.

The structures of southwest Japan are continued in the Ryukyu Island arc. The latter is distinguished by a high degree of recent and contemporary volcanic activity. The island arc of Ryukyu is limited by a deep-seated trench from Philippine Sea and is separated by the fault zones from Taiwan Island. A similar zone of faults separates Taiwan from the structures of the Philippine Archipelago in the south. As far as its tectonic properties are concerned the latter consists of the central and western zone of the earlier consolidation and younger island arcs that emerged upon the oceanic foundation.

Southwest Japan, together with the archipelago of Ryukyu, Taiwan and the Philippine, enters into the internal system of island arcs that border the Asian continent in the southeast. The external system includes younger (Cenozoic) Idzu-Bonin and Mariana volcanic arcs. The Philippine Sea is situated between the systems of arcs.

The Melanesia and New Zealand part of the Pacific belt consists of two systems of island arcs that are separated by a band of inland seas. The internal, or the New Guinea-New Zealand, system adjoins the Australian platform in the west, thus becoming separated from it by a foredeep. The structures of the external island arc include Bismark Archipelago, Soloman Islands, New Hebrides, Fiji Islands, and Tonga-Kermadec arc, to the south of Australia and New Zealand the Pacific belt extends towards the Antarctic continent.

The folded system of Andes separates the South American platform from the Pacific Ocean, and comprises the south-eastern part of the Pacific belt and is itself divided into separate zones. The northern zone – latitudinal Coast Ranges of Venezuela form the southern flank of the Antilles Island arc, which fringes the Caribbean basin. They have an arch-folded structure. The Northern Andes of Columbia and Ecuador form a bundle of anticlinoria and synclinoria of the meridional extension that widens towards the north. They are separated by a

transverse depression from the Central Andes and by a foredeep from the Guiana shield.

The Central Andes are divided into their northern and southern parts, the distinction between which lies in the history of their development and structure. On the whole the young formations (Mesozoic-Cenozoic) of the Central Andes are characterized by an inconsiderable dislocation mainly of block type. The Southern Andes differ from the Central Andes by a considerable width decrease of mountain structure and the complication of structure. There is a development of gently sloping overthrusts directed towards the Magellan trough, which separates the Andes from the Patagonia plate.

The north-western part of the Pacific belt is represented by the folded system of the North American Cordilleras, which is much wider and more complex than the Andes. This system has a fairly consistent transverse zonality and according to its structural features it is longitudinally divided into four sectors: Alaska, Canada, the USA, and Mexico. The Cordillera geosynclinal system proper is divided into the eastern and western regions. The eastern, or the miogeosynclinal region, comprises the Rocky Mountains of Canada and the USA. It is separated from the platform by foredeeps. The western (eugeosynclinal) region of the Cordilleras is wider and much more complicated than its eastern part. It includes the formations of marginal seas, island arcs, and deep-water trenches.

In the north the system of Cordillera joins the structures of Northeast Asia through Chukotka and Bering Seas. In the south the communicative function between the Cordilleras and the Andes is performed by the Antilles arcs of the Coast Ranges of Venezuela and Cordillera de Lipida.

The Arctic folded geosynclinal belt is most clearly expressed in the northern periphery of North America and Asia. In North America it includes the Innwit folded geosynclinal system of Middle Paleozoic age. In Asia the Novosibirsk-Chukotka system of the Arctic belt is distinguished.

The Young Platforms (Plates). In some parts of the geosynclinal belts of the Phanerozoic period the extinction of orogenic regime was accompanied by a gradual subsidence. The overall sinking of the folded basement of young platforms with the deposition of a continuous sedimentary cover attained its highest degree of development in the Jurassic period, at the same time with the beginning of basin formations in newly-formed oceans. This kind of sedimentary cover usually continues beyond the boundaries of continental land into the boundaries of the shelf or shelf seas.

In North America the largest young platform is the Mexico-Atlantic plate. Its foundation is essentially of Hercynian age, though there are some parts of it that are of older age (even that of the Baikal system). The maximum thickness (10-12 km) is registered in the periphery of the Gulf of Mexico and at the edge of the Atlantic submarine margin of the continent. In Europe the largest plate is the Severomorsk-Central European syneclise. It emerged upon the basement of different age, including the Baikal, Caledonian (in the north) and Hercynian (in the south) periods. Large young platforms within the confines of the USSR include the Scythian, Turan, and West Siberian plates discussed earlier.

Within the boundaries of southern continents there are: the Patagonian plate (to the south of the South American platform with the basement of Caledonian-

Hercynian age); the Epi-Hercynian plate of Matriba situated to the northwest of Africa; and the plate of the Great Artesian Basin of Australia, the western edge of which is superimposed upon the ancient platform.

Tectonic Zonation of Oceans and Its Characteristic Features

According to the characteristics relevant to their tectonic structure the four oceans of the world Pacific, Indian, Atlantic, and Arctic – have features that are common as well as distinct. The similarity consists in their general relationship with the world system of interoceanic mobile belts, as well as the characteristic elements of the structure and the deep constitution of the belts with the interoceanic plates fringing them. The distinction is brought about by the structural position of interoceanic mobile belts typical of each ocean, the interrelationship of interoceanic plates with contemporary active marginal regions, the relationship of the systems of faults with the structures of continents and zones of transition from continents to oceans, the presence and characteristic features of such tectonic elements as volcanogenic arched and block uplifts, etc.

The Pacific Ocean. It is distinguished from other oceans by its greatest area; the East-Pacific ridge is moved to the southeast and east, but has no median position of the interoceanic mobile belt; it is framed by active oceanic margins of practically the whole perimeter; it has extremely high level of contemporary volcanic activity, as well as by the heterogeneity of the structure of oceanic bed.

In many respects the structure of the ocean is controlled by the East-Pacific mobile belt (ridge). In the axial part of the ridge the absolute marks are 2 500-3 000 m; sometimes they go down to 900-1 500 m. The amplitude pertinent to the rise of the ridge above the surrounding basins varies from 2 000 to 4 000 m.

The subparallel transform faults divide the East-Pacific ridge into individual blocks that are displaced with respect to each other. The amplitude of the shift changes from 20 to 300 km and more. The transform faults control the basic features relevant to the tectonics of the floor. Their extension is greater than 1 500-2 000 km.

The structure of the two fringing regions of the East-Pacific ridge is markedly different. The southeast region occupies a rather small area between the ridge, South America, and the Antarctic continent. This is where the oceanic crust of the Cenozoic age is predominantly spread. The western area covers the major part of the Pacific Ocean. The parts of ancient oceanic plates are mainly composed of the Mesozoic crust. In the western region volcanogenic ridges, arched and block uplifts of oceanic crust are widely spread. They are rarely found in the southeast region.

As far as its structure is concerned the southeast region represents a series of relatively gently sloping troughs (Guatemala, Peru, and Bellingshausen varieties), divided by the ramifications of the East-Pacific ridge. The structure of the western region is characterized by the distribution of tectonic elements of various types and a marked heterogeneity of the oceanic crust.

The heterogeneity is established according to the character of the anomalies of magnetic field, where alongside the banded anomalies there are sections of calm magnetic field. Besides, the western region is characterized by the presence of numerous tectonic elements of various kind.

The Indian Ocean. As distinct from the Pacific Ocean the Indian Ocean is fringed by the blocks of ancient platforms along the whole perimeter. The interoceanic mobile belt of the Indian Ocean consists of three ridges: the Australian-Antarctic, Arabian-Indian, and African-Antarctic ones. These ridges are distinguished by their width and absolute marks. The Arabian-Indian ridge is the one that is most markedly expressed in the relief. The transform faults that intersect the ridges are variously oriented in some parts of the territory. The shift dislocations along the faults usually comprise 50-100 km.

There are three regions that fringe the mobile belt of the Indian Ocean. These regions are almost similar to the age of the oceanic crust, but are different in their structure. The southern region is relatively simple as far as its structure is concerned. Here two somewhat gently sloping basins are distinguished. They are confined to the Australian-Antarctic and African-Antarctic basins that are divided by the arched uplift of the Kerguelen Island. The northeast region is characterized by the heterogeneity of oceanic crust and the presence of extended (up to 5 000 km) block uplifts, or the Maldive and East-Indian ridges. The heterogeneity of oceanic crust finds its expression in the presence of various tectonic elements and banded magnetic anomalies. The western region differs from the others by the presence of two blocks of continental crust (microcontinents) – Madagascar and the Seychelles Islands in the central part. The quiet magnetic field is found to spread over the greater part of the region. The banded anomalies of the magnetic field have been established in certain parts of the Somali and Mozambique basins.

The Atlantic Ocean. By the character of bordering it has very much in common with the Indian Ocean. The main characteristic feature of its structure consists in the median position of the interoceanic mobile belt – the Middle Atlantic ridge. This was precisely what determined the symmetry of the tectonics of the Atlantic Ocean, which is particularly apparent to the south of 55° N, where the Charley-Gibbs transform fault is extended.

The structure of the Middle Atlantic ridge is not the same in different parts. The amplitude of the ridge rise over the surrounding basins comprises over 2 000 m to the south of the Charley-Gibbs fault, and approximately 1 000 m to the north. The extension of the ridge is in conformity with the linear anomalies of the magnetic field. The transform faults split the ridge into separate blocks that are displaced with respect to each other. The shifts are 25-50 km, and sometimes as great as 100-250 km. In a large number of cases transform faults are continued on the continents.

The northern region of the Atlantic Ocean is situated to the north of the Charley-Gibbs fault. This is where series of perioceanic troughs of complex form and relatively small size are found. The western and eastern areas are situated on either side of the ridge to the south of the Charley-Gibbs fault. They have almost the same tectonic structure and are characterized by the presence of large perioceanic troughs that are confined to the basins.

The Arctic Ocean.The structure of this ocean is characterized by most essential heterogeneity, by the absence of active oceanic margins, and by the very young age of the interoceanic mobile belt, or the Gakkel ridge. The heterogeneity of oceanic bed finds its expression in the presence of two different tectonic regions – the Eurasian and Amerasian ones. The structure of the former is regulated by the Gakkel ridge and is characterized by a typically oceanic crust. The Amerasian region represents the alternation of blocks of oceanic, continental, and suboceanic types of crust with the predominant role of Lomonosov and Mendeleyev-Alpha ridges.

The Gakkel ridge differs from the other interoceanic mobile belts by a small length, width, and the height of the relief. The amplitude of the rise of the ridge over the surrounding basins reaches 1 000-2 000 m. The transform faults are situated at the distance of up to 50 km from each other. The amplitude of shifts does not exceed 20-30 km.

The analysis of the tectonic map of the world shows definite regularities in the distribution of oceans and continents. The most significant feature of the distribution is the existence of oceanic (occupied by the Pacific Ocean) and continental (with the inclusion of the Atlantic and the Indian Oceans) hemispheres of the Earth. Moreover, the distinctions between the Arctic and the Antarctic regions may well be considered to be relevant. The former is occupied by the aquatorium of the Arctic Ocean in the centre with the continental bordering along the periphery. The latter region is occupied by the Antarctic Continent, washed by the waters of the Indian Ocean.

Lastly, the relatively predominant role of continents in the Northern Hemisphere, and that of oceans in the Southern Hemisphere attracts our attention. It is assumed that the sources of this asymmetry are connected with the factors external with respect to the Earth itself, rather than with the initial heterogeneities of the substance entering into the composition of the Earth.

The symmetry in the distribution of oceans and continents is expressed in the existence of two basic latitudinal belts of the continents (with platform cores), viz. the north and the south ones, which are separated by the belts of aquatoria, as well as in the continents grouping into longitudinal belts (Asia-Australia-Antarctica).

In the analysis of the tectonic structure of the earth's crust there evidently emerges the contrast between continents and oceans. Thus, there exist divergencies in the composition of the crust that are conditioned by a comprehensive development of granites and gneisses on continents and their absence in oceans. The oceanic crust is exclusively distinguished by the young age of formation. The structure of continents is characterized by great complexity as against the relative simplicity typical of the structure of oceans. What can also be attributed to the oceans is a wide development of the rift structures of the gaping fault type, the function of which follows within the boundaries of continents.

One more thing that deserves our attention is the network of deep planetary faults that is superimposed upon the structures of oceans and continents. In addition to this the geometry of this network in the oceans is found to be more simple: extended gaping faults in the rift zones of the mid-oceanic ridges and the transform faults perpendicular to them. The global network of faults manifests a

certain orientation with respect to the figure of the Earth's rotation.

The regularities in the constitution of the lithosphere that have been discussed can find a satisfactory explanation on the basis of genetic constructions, which take into account the whole set of modern geological and geophysical data.

Chapter 19 Tectonic Zonation and Geological Structure of the USSR

Main Features of the Tectonic Structure and the Relief of the USSR

Principles of Tectonic Zonation.The Soviet Union is mainly a continental country, that is why the tectonic zonation of its territory is essentially the division of the greater part of the Eurasian continent into individual structural elements, viz. platforms and folded regions. The territory of the USSR is characterized by the great variety and complexity of its geological structure, which, in its generalized form, is represented on the tectonic map. Up to the present moment several variations of the tectonic map of the USSR have been compiled, in which the basic ideas of different geological trends have found their expression. Those of greatest interest are the maps edited by N. Shatsky, N. Belyavsky, A. Bogdanov, M. Muratov, A. Peive, V. Khain, and A. Yanshin. In the present book the tectonic zonation of the USSR territory is given in accordance with the simplified variant with the current ideas and most recent data taken into account. They are reflected in the detailed tectonic maps that were published for the XXVIIth International Geological Congress held in Moscow in 1984.

The main principle of the USSR tectonic zonation consists in the singling out of regions by *the age of folding*, i.e. according to the time related to the transformation of a folded geosynclinal region into a platform. This principle, which was formulated by N. Shatsky, has recently been supplemented (A. Peive, A. Yanshin, L. Zonenshain, and others) by the idea of distinguishing the regions in compliance with the time of the final development of the granitic layer, based on the concept of the oriented geosynclinal development of the earth's crust from the crust of oceanic type to that of the continental variety.

On the tectonic map of the USSR (Fig. 100), and in accordance with the principle that has been expounded above, the following folded areas are distinguished* (figures in brackets show their position on the map).

I. Pre-Cambrian (pre-Late Proterozoic) East European (1) and Siberian (2) platforms.

II. The Baikal (Late Proterozoic) Timan-Pechora (3), North Taimyr (4), Sayan-Enesei (5), and Baikal (6) platforms.

* On the tectonic maps some regions with a complicated geological structure (Taimyr, Scythian plate, Mongol-Okhotsk, etc.) can be referred to other zones of folding than those given below in accordance with various concepts adhered to by the authors of maps of the tectonics of individual regions.

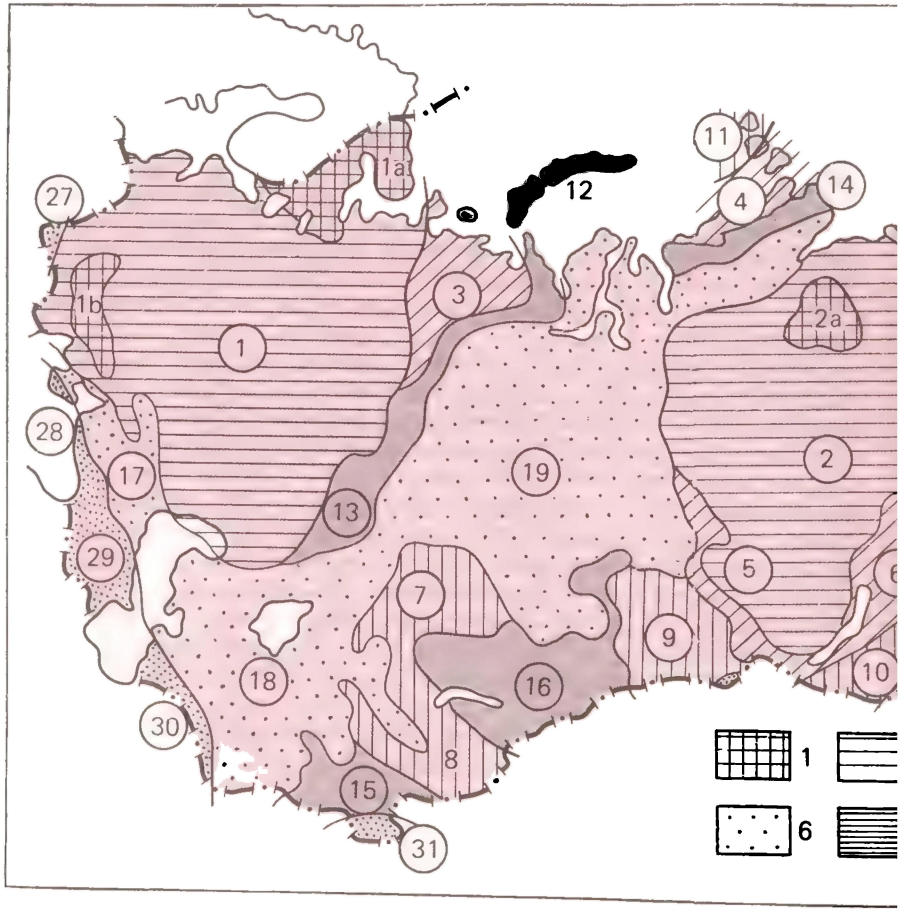
III. Caledonian (Early Paleozoic) – the western part of Central Kazakhstan (7), North Tien Shan (8), West Sayan and Kuznetsk Alatau (9), Selenga-Yablonevaya (10), and Severnaya Zemlya (11) platforms.

IV. Hercynian (Late Paleozoic) - Novaya Zemlya (12), Ural (13), South Taimyr (14), South Tien Shan (15), the eastern part of Central Kazakhstan and Altai (16) platforms; Epi-Hercynian plates – Scythian (17), Turan (18), and West Siberian (19) ones.

V. Mesozoic Verkhoyansk-Chukotka (20), Mongol-Okhotsk (21), Sikhote-Alin (22) platforms; median Kolyma (23), Omolonsk (24), Okhotsk (25), and Burea (26) platforms.

VI. Cenozoic (Alpine) Mediterranean belts – East Carpathian (27), Mountainous Crimea (28), Caucasus (29), Kopet-Dag (30), and Pamir (31) platforms.

VII. The Cenozoic folded regions of the Pacific belt – Kamchatka-Koryak (32), Kuril and Komandorskiye Islands (33), and Sakhalin (34) platforms.



Geosynclinal regions of different age are brought together into three fold belts that divide and fringe the ancient platforms: the Ural-Mongol belt of Paleozoic folding, in which the formation of continental crust was accomplished; the Mediterranean Alpine folding, the Pacific Mesozoic and Cenozoic types of folding, where the earth's crust formation continues.

The Relief.The variation in the tectonic structure is conditioned by the complexity and diversity of the relief of the country's territory. The relief of the USSR includes highland zones (15% of the area), vast plains, lowlands, high plateaus, and uplands. The difference in heights within the confines of the USSR territory comprises more than 7 600 m; the highest point is the Communism Peak (7 495 m) in the Pamirs, and the lowest one is the Karagiye depression (– 132 m) in the Mangyshlak Peninsula in the Caspian region.

The territories of the plains and lowlands correspond to the ancient (East European, Siberian) and young (Western Siberian and Turan) platforms. The

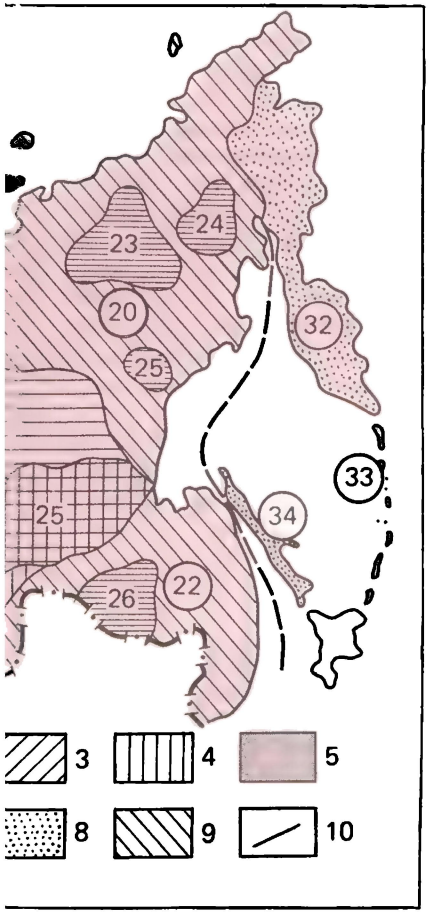


FIGURE 100. Tectonic zonation of the USSR:

1 – shields on ancient platforms; *2* – zones of Pre-Cambrian folding under the platform mantle; *3* – zones of Baikal (Riphean) folding; *4* – zones of Caledonian folding; *5* – Hercynian mountain-folded zones; *6* – plates of Epi-Hercynian platforms; *7* – median massifs in the zones of Mesozoic folding; *8* – zones of Mesozoic folding; *9* – zones of Alpine folding; *10* – the boundary of regions

elevated parts coincide with the positive structures of platforms – shields, anteclises, and uplifts, while the depressions of the relief are also confined to the piedmont and intermontane plains, basins, and syneclises.

The Alpine relief is characteristic of the regions of Mesozoic and Cenozoic folding, as well as of the southern part of the Ural-Mongol belt, which had undergone epiplatform orogenesis. The Alpine belt in the southwest and south of the USSR includes the Cenozoic structures of Eastern Carpathians, the Mountainous Crimea, the Caucasus, Kopet-Dag, and the Pamirs. The highest altitudinal marks are typical of the mountain peaks of the Minor Caucasus (Aragats – 4 095 m), the Major Caucasus (Elbrus – 5 633 m, Kazbek – 5 047 m), and the Pamirs (Communism Peak).

Within the confines of the Urals the Paleozoic folded regions have relatively low marks registering the height (Narodnaya – 1 894 m, Yurma – 1 002 m), while in the South of the USSR, where epiplatform orogenesis was manifested, they form part of the system of the Alpine framing of the USSR (Lenin Peak – 7 134 m, Pobeda Peak – 7 439 m in Tien Shan; Belukha – 4 506 in Altai).

In the north-eastern part of the USSR Mesozoic folded structures find their expression in mountain ridges (Verkhoyansk, Chukotka, Anyui, Cherski) and the altitudinal marks 2 500–3 000 m (Mount Pobeda – 3 147 m, Cherski Mountain Range). In the east of this country Cenozoic folded structures of Kamchatka, Sakhalin, Kuril Islands are characterized by a highly dissected relief with the difference in heights from 200 to 1 500-3 000 m. The highest points are the mud volcanoes of Ichinskaya (3 627 m), Klyuchevskaya (4 850 m), Avachinskaya (2 731 m) in Kamchatka, the Alaid volcano (2 339 m) in Kuril Islands, the Lopatin Mountain (1 609 m) in Sakhalin.

The present-day relief of the USSR territory is the result of a complex interaction of denudation and orogenesis. Marked irregularities of the relief, created in the Pre-Cambrian, Paleozoic and partly in Mesozoic periods were levelled out as a result of denudation. The Alpine relief is the result of Cenozoic movements that continue even now.

In what follows we have a brief geological characteristic of the basic structural elements of the earth's crust distinguished within the boundaries of the Soviet Union. Maximum attention is paid to those regions* within the confines of which deposits of mineral resources are distributed.

Ancient Platforms (Regions of Pre-Cambrian Folding)

In the USSR ancient platforms cover a substantial territory. The East European and Siberian platforms represent stable blocks of the continental crust. The crystalline foundation of platforms was formed at the end of the Early

* In description of the geological structure of the regions the authors have mainly employed the materials contained in the books 'Fundamentals of the Geology of the USSR' by M. Smirnova, and N. Koronovsky's 'Concise Course in the Regional Geology of the USSR' (in Russian).

Proterozoic period, while the development of the folded cover goes back to the Late Proterozoic period.

The East-European (Russian) Platform. It occupies the territory of eastern, western, and central Europe, and is delimited by the Alpine structures of the Eastern Carpathian Mountains from the southwest, while Paleozoic structures restrict it from all other sides. The platform contains the following structural elements*: *shields* – the Baltic shield (see Fig. 100), the Ukrainian shield (1b); *aulacogenes* – Pachelma, Moscow, Dnieper-Donetsk types; *anteclises* – Byelorussian, Voronezh, and Volga-Ural varieties; *syneclises* – Moscow, Baltic, Black Sea, and Caspian Sea regions; the Main East-European *deep fault.*

The average thickness of the earth's crust within the confines of the platform is 35-40 km. The maximum thickness is 50-55 km (the Ukrainian shield and the Voronezh anteclise); the minimum thickness is equal to 20-24 km (the Caspian Sea syneclise). The sectional view of the platform is illustrated in Fig. 101.

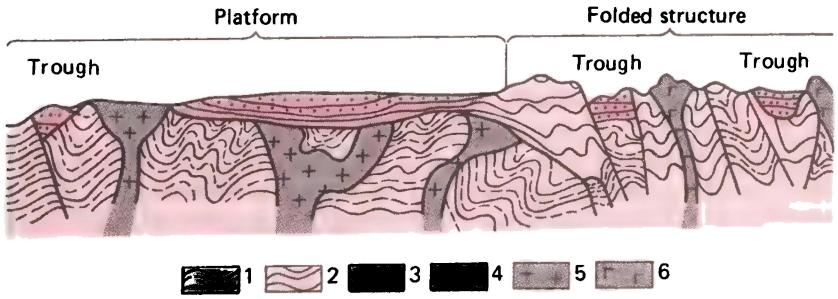
The basement of the East-European platform is considerably dissected (the difference in heights makes up to 5 km) and is composed of deeply metamorphosed Archean and Lower Proterozoic formations: e. g. gneisses, crystalline schists, amphibolites, ferruginous quartzites, and marbles. Metamorphic masses are pierced through by the intrusions of granites, gabbro, and diorites.

The structure of the platform basement has been most profoundly studied in shields. In the eastern part of the Baltic shield there is the Archean Belomor massif, which is separated from the Kola and Karel zones by deep faults. In the southern zone of the massif (the east coast of White Sea) volcanic pipes are known to exist. In the Baltic shield we find the development of intrusions of nepheline syenites and apatite-nepheline rocks.

A similar deep structure is typical of the Ukrainian shield, where the Dnieper and Podolsk massifs are distinguished. The Pre-Cambrian period is represented by the metamorphic mass of schists, conglomerates, and ferrugenous quartzites;

FIGURE 101. A sectional view of the East European platform and the Ural folded structure:

1 – Pre-Paleozoic deposits; *2* – Paleozoic deposits within the confines of folded structure; *3* – Paleozoic deposits; *4* – Meso- and Cenozoic deposits; *5* – Pre-Paleozoic intrusions; *6* – Paleozoic intrusions



* Here and elsewhere only the main structural elements are discussed.

the development of granite intrusions, and more seldom basic rocks, is found to be a typical feature. The territory of the Russian plate is characterized by the same complicated internal structure of the basement. Numerous Archean massifs corresponding in some cases to anteclises and in others to syneclises have been established.

The region where Late Proterozoic and Cenozoic sedimentary cover is spread is known for its complex structure and a dissimilar fullness of the section in different structures of the Russian plate. The Upper Proterozoic (Riphean) fragmental deposits are present in the graben-like troughs – aulacogenes - and have a fairly great thickness.

Sandy-clay Cambrian deposits are developed within the confines of syneclises. The deposits of Ordovician and Silurian periods have been discovered in the Baltic and the Dniester regions. They are represented by sandy-schistose (including combustible schists as well) and carbonate (limestone, dolomite, and marl) masses. The Devonian and Carboniferous deposits are developed everywhere. They are formed by sandy-clay, gypsum-anhydrite, saliferous rocks, limestones and dolomites. In the lower part of the section the Permian system is composed of terrigenous, carbonate and halogen rocks, while sandstones, clays, marls, and dolomites cemented by gypsum constitute the upper part. The deposits of the Triassic period, viz. red sandstones, clays, marls, conglomerates, and carbonate rocks, can be found only in the Moscow, Baltic and Caspian syneclises, and in the Volga-Ural anteclise.

The propagation of Jurassic deposits is fairly comprehensive. They are represented by coal clays, sandy-clay rocks, sandstones with nodules of phosphorites, and combustible schists. Within the section of Cretaceous deposits there is the presence of sandy-clay, carbonate (limestones, chalk, and marl) and siliceous (opokas and tripoli) rocks. Cenozoic (bedrock) deposits are known in the southern part of the Russian plate, where they are represented by sandy and sandy-calcareous masses. Among the Quaternary formations there is a preponderance of glacial, alluvial, and marine deposits.

The Voronezh anteclise represents a gentle uplift elongated in the same way as the Ukrainian shield and close to it in size. In the most elevated part of the anteclise the Pre-Cambrian foundation occurs at the depth of 50-200 m, and in some places it comes out onto the surface. The structure of the foundation involves the participation of iron-ore formation of rocks. *The Byelorussian anteclise* of the western part of the platform is composed of rocks of Cambrian, Ordovician, Silurian and Middle Devonian periods. The deposits of Quaternary system are characterized by considerable thickness. *The Volga-Ural anteclise*, which occupies the whole western part of the platform, is complicated by arches that are divided by depressions and troughs. Within the arches the foundation is deposited at the depths ranging from 1 000 to 2 500 m, while in the troughs it subsides down to 3 000 m and more. In the structure of the geological section of the sedimentary mass no minor importance is attached to the rocks of the Permian system.

In *the Moscow syneclise* the occurrence depth of the basement reaches 3 km. The sedimentary cover is composed of deposits of Devonian, Carbonaceous and Permian periods; the Mesozoic formations manifest themselves but sparingly,

while the Cenozoic ones find their expression only in Quaternary deposits. The Caspian syneclise is distinguished by a marked depth at which the basement is deposited (15-20 km). The sedimentary mass is composed of Carbonaceous, Permian, Mesozoic and Paleogenic deposits. The characteristic feature of this structure is a comprehensive development of saline domes (numbering over one hundred) of the Early Permian age.

The Baltic syneclise is superficially composed of the deposits of the Cretaceous period, which, in the west, are overlapped by those of Paleogenic type. The sedimentary cover is filled with a thick mass of rocks of Upper Paleozoic, Mesozoic, and Cenozoic periods. The basement is subsided to the depth of more than 2000 m.

The Dnieper-Donetsk aulacogene (trough) is the most complicated and large one on the platform. Devonian (saliferous), Carboniferous, and Permian deposits overlapped by Meso-Cenozoic formations, take part in its structure.

Great significance in the structure and development of the platform belongs to *the Main East-European deep fault*, which is extended in the meridional direction. It divides the platform into two parts: the uplifted western part and the lowered eastern one.

Mineral resources of the East-European platform are connected with its basement and platform cover. Deposits of iron ores in the Ukrainian shield, the Voronezh anteclise, and the Baltic shield may well be correlated with the Pre-Cambrian formations of the foundation. Copper and nickel deposits can be associated with the Proterozoic basic and ultrabasic intrusions of the Baltic shield. Deposits of muscovite and phlogopite can also be found. The apatite-nepheline deposits of Khibiny correspond to the alkaline massifs on the Baltic shield. Within the confines of the Ukrainian shield one can find the relationship between the Pre-Cambrian formations and the deposits of graphite. Magmatic and metamorphic rocks (granites, gabbro, and quartzites) of the basement are of no small value as natural stone building materials.

The sedimentary cover of the platform is connected with the deposits of caustobioliths, chemical, agricultural and some metallic ores, as well as building materials. Among the hard caustobioliths the main importance is shared by fossil coals, which are confined to Carbonaceous and Paleogenic deposits. Combustible schists are connected with the Ordovician and Jurassic deposits. Peat is found to be widely spread in the west and north of the platform.

Oil and gas bearing provinces and deposits can be singled out within the boundaries of the Volga-Ural and Ural-Emba regions, the Dnieper and Donetsk basin, the Pripyat depression, and the Baltic syneclise. Deposits of rock and potassium salts (Starobinsk, Iletsk, Solikamsk, and Verkhnekamsk) are connected with the Devonian and Permian deposits of the platform. Phosphorite deposits (Baltic Sea regions, Moscow, and the Volga region) are situated in the Lower Paleozoic, Jurassic, Cretaceous, and Paleogenic deposits.

Among the ore deposits those of no minor interest are the ones of iron (Tula and Lipetsk regions), manganese (Nikopol, Bolshetokmak), aluminium (Tikhvin bauxite). Deposits of kaolin, refractory clays, cement deposits and other materials used for construction purposes are spread within the confines of the platform.

The Siberian Platform.Its area is very much the same as that of the East-European platform and covers a considerable part of the Central Eastern Siberia. From the northwest, west and south the Siberian platform is delimited by baikalides; by hercynides from the north, and by the Mesozoic folded formations from the east. The main structural elements of the platform are: *shields* – the Anabar (see Fig. 95, *2a*) and the Aldan (*2b*) shields; *elevations* (anteclises), the Anabar, Olenek, Munsk, Khatanga, and Ilim varieties); *syneclises* and *basins* of the Tunguska, Khatanga, Vilyui, Angara-Lena, Irkutsk, and Kansk types; *aulacogenes* (Udzhinsk, Irkineyev, Urin); and the Trans-Siberian *deep fault*. On the greater part of the platform the thickness of the earth's crust comprises 35-40 km. The maximum thickness of the earth's crust (40-45 km) is found in the southern part of the platform on the border with baikalides; the least degree of thickness (30 km) is registered in the northern part of the Tunguska syneclise.

The basement of the Siberian platform is characterized by a markedly dissected relief. It comes out onto the surface within the confines of the shields, its subsidence in the marginal parts of the shields is not deep, and it goes down to the depth of 8-10 km in syneclises. The Pre-Cambrian formations of Archean and Low Proterozoic periods are represented by gneisses, quartzites, amphibolites, high-alumina crystalline schists, and marbles. A considerable role is attributed to large granitoid intrusions. The sub-meridional Trans-Siberian fault divides the basement into two huge blocks, the eastern one of which is composed of more ancient formations.

The Anabar shield is the core of the anteclise bearing the same name. It is constituted of deeply metamorphosed rocks crumpled into folds. *The Aldan shield* is characterized by an asymmetrical structure: its northern wall is gently sloping, while the southern one is torn off by the fault. Markedly dislocated magmatic and metamorphic rocks are exposed on the surface of the shield.

The platform mantle is composed of the Upper Proterozoic, Mesozoic, and Cenozoic deposits. The Upper Proterozoic type is represented by carbonate and terrigenous deposits (sandstones and gritstones). The Cambrian system is contributed by clay limestones, dolomites, anhydrites, saliferous and bituminous rocks, clays, sandstones, and marls. Deposits of Ordovician and Silurian periods are developed throughout the whole area of the platform and are represented by terrigenous and carbonate rocks. The Devonian period is represented in the complete section by limestones and dolomites with the interlayers of gypsum-bearing and sandy-clay rocks. The characteristic feature pertinent to the structure of sedimentary cover is a comprehensive development of continental carboniferous deposits of Middle and Upper Carbonaceous and Permian periods, or the so-called Tunguska series. Its content is conditioned by the alternation of sandstones, schists, aleurolites, and the interlayers of hard coal.

The overlying mass of the Triassic age is represented by tuffaceous (tuffs, tuff conglomerates, tuff sandstones, aleurolites, sandstones, and schists) and welded tuff formations. The latter are represented by sheet of basalts and dolerite-porphyries with interlayers of tuffs, tuff sandstones, and sandstones, as well as by the intrusions of diabases and gabbro-diabases. Intrusive and effusive

formations of the basic composition on the Siberian platform are called *traps*. The choice of the term was conditioned by a characteristic columnar jointing of rocks and the step-like form of the relief. Traps are connected with volcanic pipes filled with kimberlites. The Jurassic and Cretaceous deposits find their expression in clastic rocks and interlayers of limestones in the north and fossil coals in the south. The Cenozoic deposits are found to be not characteristic of the platform.

The structure of sedimentary cover is inherited by the structures of basement: anteclises correspond to the protrusions of the Pre-Cambrian basement; on the other hand, syneclises may well be correlated with the depressions in the basement relief. *The Anabar anteclise* is situated in the peripheral parts of the Anabar shield, while in the northern part we have *the Popigai ring structure*. Its origin is associated either with the processes of volcanism, or with the fall of a gigantic meteorite (astroblem).

The Tunguska syneclise is the most prominent structure of the Siberian platform mantle (with its area covering more than 1 mln km^2). The syneclise is filled with a many kilometre thick mass of rocks. Traps and volcanic pipes are widely spread in the sedimentary cover. The basement of the syneclise is fractured by a system of sublatitudinal faults. The peripheral part of the syneclise is complicated by ring and linear tectono-magmatic structures with which cross intrusive sheets of dolerites are correlated.

The Vilyui syneclise situated in the east of the Siberian platform is the deepest negative structure (the depth of basement arrangement is more than 10 km); the sedimentary cover of the syneclise is complicated by saline domes (of the Devonian age), and its dimensions reach 30 km.

The Khatanga syneclise is extended along the northern boundary of the platform in an arch. It is filled with Upper Paleozoic, Mesozoic, and Cenozoic formations. The basement (according to the data of seismic studies) is deposited here at the depths of 7-8 km. The Irkutsk depression and the Angara-Lena trough frame the platform from the south. They are characterized by the relatively simple synclinal occurrence of rocks pertaining to the Jurassic carboniferous mass.

The mineral resources related to the basement of the Siberian platform are represented by ores of nonferrous and rare metals, iron, and micas. In the Archean deposits of the Aldan shield there are ferrigenous quartzites. The Lower Proterozoic deposits of the Aldan shield are connected with the Udokan deposit of cuprous sandstones. Apatite deposits are connected with the Archean formations of the Aldan shield. Pegmatite deposits also tend towards the Pre-Cambrian rocks of the basement.

The sedimentary cover is remarkable for the presence of caustobioliths, deposits of iron complex ores and nonmetallic raw materials. In the southern part of the Tunguska syneclise there is the Angara-Alim iron ore basin. The sulphide copper and nickel deposits are related to Siberian traps. There exists relationship between gold-bearing deposits and the Jurassic intrusions of acid and basic composition. The deposits of salts (Usol, Olekminsk) are associated with Cambrian depositions. Those of graphite can be found in the lowlands of Enisei. The deposits of bauxites and phosphorites are connected with sedi-

mentary and volcanogenic rocks; and there is a close link between traps and alkaline intrusions and Iceland spar.

The Tungus coal-bearing basin (the Tungus series), as well as Irkutsk, Kansk and South Yakutsk ones, are known to be situated within the boundaries of the Siberian platform.

Regions of the Baikal Folding

In the structure of the regions remarkable for the Baikal folding (baikalides), the main role belongs to the Pre-Cambrian masses, which are intensely metamorphosed and crumpled into complex linear folds. They give rise to a complex of basements of baikalides and are represented by gneisses, crystalline schists, and the cut-off intrusions of gabbro-anorthosites and granitoids. Within the section of the geosynclinal complex various sedimentary and volcanogenic and sedimentary rocks of the Upper Proterozoic period are developed. The Orogenic Baikal complex is composed of fragmental masses. The platform mantle is composed of Paleozoic, Mesozoic, and Cenozoic deposits. The connection of the Baikal folded systems with the Pre-Cambrian platforms takes place along the deep faults, which are usually well expressed in the relief.

The Timan-Pechora Region. This region covers the territory of the Mainland tundra to the northeast of the East European platform. Some scientists refer this region to the East European platform, others consider it to be the Epi-Baikal plate. The basic structural elements of the region are the Timan elevation and the Pechora syneclise.

The Timan elevation represents a system of meridionally elongated folds. The ancient deposits are intensely dislocated. The overlapping Paleozoic deposits form a system of gently sloping box-folds. The Pechora syneclise is composed of a thick mass of sedimentary formations of the Paleozoic and Mesozoic periods. The basement is subsided to the depth of 5-6 km.

The mineral resources of the Timan-Pechora region are oil, gas and gas-condensates, the deposits of which are confined to the swells and uplifts and occurred practically in all the deposits of the cover. In Timan bauxites are related to Devonian deposits.

The Sayan-Enisei Region. This region includes the structures of the Enisei mountain range and the folded structures of the Eastern Sayan Mountains, which form the southwest frame of the Siberian platform. From the west and east the Enisei mountain range is delimited by systems of deep faults. The basement of the structure is composed of the Archean and Early Proterozoic metamorphic rocks; the geosynclinal complex is represented by Late Proterozoic terrigenous and carbonate rocks. Bodies of hyperbasites can also be found here. The elevation of Eastern Sayan is composed of thick geosynclinal masses of the Proterozoic period and has a clear-cut block structure.

The Sayan-Enisei region is rich in various mineral resources. In the eastern part of the Enisei elevation we have the Angara-Pitsk iron ore basin connected with the Cambrian deposits, the deposits of molybdenum, manganese deposits correlated with granitoids, as well as deposits of bauxites and polymetals.

Deposits of asbestos are confined to intrusive and effusive formations. Graphite is known to be deposited in Eastern Sayan.

The Baikal Region.This enormous wedge-like region is incised into the southern marginal part of the Siberian platform. It is constituted by thick masses of metamorphic rocks of the Archean and Proterozoic periods. The Upper Proterozoic (Riphean) deposits of the Baikal region are markedly dislocated. This region is crossed by the zone of Baikal rift, which is characterized by active contemporary geological processes and a very high degree of seismicity. Within the confines of the Baikal folded region there are deposits of lead and zinc (of the pyrite variety), tungsten, molybdenum, asbestos, fluorite, and oil.

Regions of Paleozoic (Caledonian and Hercynian) Folding

The regions of Caledonian and Hercynian folding, forming the Ural-Mongol Paleozoic belt, divide the East-European, Siberian, Tarim, and Chinese platforms (see Fig. 100). The main structures of the basement are large provinces, which include the Urals, Tien Shan, Central Kazakhstan, Altai, and Sayan Mountains. The structures of platform mantle comprise Epi-Hercynian platforms (plates), e. g. West Siberian, Turan, and Scythian ones.

In the caledonide structures marine Cambrian and Ordovician sedimentary, and sedimentary-volcanogenic rock masses are widely spread. They are crumpled into complex linear folds. The Caledonian orogenic complex includes deposits of the Upper Silurian and Devonian periods, represented by terrigenous formations, while the deposits of the Mesozoic and Cenozoic periods are found to be characteristic of the platform complex.

In the regions of Caledonian folding there are several complexes of magmatic rocks and the deposits associated with them. Chalcopyrite deposits are associated with the Cambrian volcanogenic rocks. In the serpentinous massifs of peridotites and gabbro there are deposits of asbestos, talc, and magnesites. Granodiorites are the sources of hydrothermal deposits of nickel and cobalt and polymetallic ores. Intrusions of leucocratic granites are accompanied by the formation of pegmatites, greisens, and quartz veins with wolframite and molybdenum.

The Hercynian folded structures are widely spread in the Ural- Mongol belt. They are formed, in the main, by geosynclinal sedimentary and volcanogenic formations of Lower Paleozoic, Devonian, and Lower Carboniferous brought together into linear folds and broken through by large granitic masses (Upper Carboniferous and Permian periods). The Mesozoic complexes are usually represented by marine and continental terrigenous deposits of the platform type.

The regions of Hercynian folding, which are characterized by complex geological structure, comprehensive development of magmatic formations of different age and composition, are distinguished by an unusually great variety of mineral resources. This is where we can find contract-metasomatic deposits of iron ores (Altai, Ural), hydrothermal deposits of polymetals, tin, tungsten-molybdenum and copper ores (Altai, Kazakhstan), deposits of bauxites (Ural),

chrysotile-asbestos and micaceous deposits. Coal-bearing basins are also characteristic here.

Of all the structures of the Ural-Mongol folded belt only the Ural variety is a completely Hercynian structure. The others represent *mixed Caledonian and Hercynian structures.*

The Central-Kazakhstan folded region lends itself to be classified into Caledonian and Hercynian parts. The Caledonian part includes the geosynclinal and orogenic complexes. The former is represented by anticlinoria and synclinoria, bounded by deep faults, and the latter finds its expression in depressions and troughs. Among the rocks of geosynclinal complex the basic effusive rocks, siliceous, carbonaceous, and terrigenous formations are included. Intrusives of granitoids, basic and ultrabasic rocks are also widely spread. The orogenic complex is composed of psephitic volcanogenic and volcanogenic and sedimentary rocks (molasses), carbonaceous and terrigenous and carbonaceous deposits with coal beds, red continental terrigenous masses, enclosing those of cuprous sandstones.

In the Hercynian part of Central Kazakhstan the geosynclinal complex is represented by marine formations - sandstones, and aleurolites with interlayers of limestones and volcanogenic rocks (Silurian, Devonian, Carboniferous periods). The orogenic complex of rocks (Carboniferous and Permian) are well expressed in the depressions, where it is composed of molasse. The deposits are pierced through by granitoidal intrusions.

The mineral resources of Central Kazakhstan are highly varied. The Dzhezkazgan copper ore deposit is confined to sandy-schistose mass of the Carboniferous period, as well as to the sandstones and conglomerates of the Devonian period. Magmatic rocks are connected with the Kounrad copper deposit. Tungsten, molybdenum, and tin-ore deposits are found to be related to granites of Permian age. There are carboniferous basins in Karaganda and Ekibastuz.

The Altai-Sayan folded region includes Altai, Western Sayan Mountains, the ridges of Salair, Kuznetsk Alatau, Mountainous Shoriya, partly Eastern Sayan Mountains, and the northern part of Tuva. The region consists of Caledonian and Hercynian structures. The Kuznetsk foredeep is also distinguished. According to the structure of geosynclinal and orogenic complexes the Caledonian part of the Altai-Sayan region has very much in common with the complexes of Central Kazakhstan. The Hercynian part is characterized by a more simple structure. The geosynclinal complex is represented by terrigenous formations, acid and median effusions. The orogenic complex, composed of sedimentary and volcanogenic rocks, is spread in depressions and in small areas.

The Kuznetsk foredeep is situated at the junction of Caledonian and Hercynian structures. In its structure the main role is attributed to the thick (up to 9 km) Carboniferous and Permian coal-bearing mass, which contains up to 75 operating beds of coal with the thickness of about 2 km. What overlies them is Triassic and Jurassic carboniferous deposits.

The Altai-Sayan folded region is an important ore-bearing province. This is where we find the skarn iron-ore deposits in mountainous Shoriya, Kuznetsk Alatau, and West Sayan. Polymetallic hydrothermal deposits are widely

developed in Rudny Altai. Tungsten-molybdenum deposits have been discovered in the Irtysh zone of crumpling. Manganese ores correspond to the Cambrian deposits of Kuznetsk Alatau. The antimonial-mercury deposits are correlated with the Salair and West Sayan deep faults, and chrysotile-asbestos deposits are associated with massifs of serpentinites.

The Tien Shan folded system is situated to the south of Central Kazakhstan, and, as far as its structure is concerned, has very much in common with the latter. Two branches can clearly be distinguished within it, viz. the northern branch, or Caledonian, and the southern one, or Hercynian. The basement of Caledonian structures is composed of gneisses, quartzites, and crystalline schists. The geosynclinal complex is represented by volcanogenic and sedimentary rocks of Riphean-Ordovician periods. The orogenic complex (molasses) are found in small depressions. In its Hercynian part the basement is expressed by rocks of Cambrian and Ordovician periods. The geosynclinal complex is filled with Silurian and Carboniferous deposits.

The epiplatform orogenesis was intensely manifested in Tien Shan folded system. Hence, rocks of this region, as compared with other Paleozoic structures, are more prominently elevated. Alongside the block uplifts there also emerged deep compensation neotectonic basins, of which the Fergana basin is the largest.

Tien Shan is characterized by the presence of a large number of endogenic and exogenic deposits of mineral resources. It is known that there are complex skarn and hydrothermal deposits connected with granites, molybdenum-tungsten, copper, and antimony-mercury varieties. The exogenic deposits include those of coal (Angren, Uzgen), and the phosphorite and oil ones in Fergana.

The Ural folded system extends in the meridional direction. In tectonic terms the Urals present the alternation of large anticlinoria and synclinoria; and are characterized by the constancy of the section along the strike and a rapid change of cross-section. The Ural foredeep borders directly on the East-European platform (see Fig. 101).

The Ural section consists of its basement composed of rocks of the Proterozoic period; Hercynian geosynclinal complex, covering Cambrian and Middle Carboniferous rocks; the orogenic Hercynian complex (Upper Carboniferous-Middle Triassic); and the platform complex (Upper Triassic-Quaternary deposits). The basement is composed of gneisses, conglomerates, sandstones, clay schists, phyllites, and carbonate rocks. In the structure of geosynclinal complex there participate volcanogenic, metamorphosed terrigenous and volcanogenic rocks, basic and acid effusions, limestones, jaspers, basic and ultrabasic rocks.

The orogenic complex includes masses of limestone, sandy-clay rocks, and halogen rocks; the intrusion of alkaline granites is typical.

The platform complex is composed of continental coal-bearing deposits. The Ural foredeep is filled with a thick mass of mallasses, formed at the expense of the removal of clastic material from the Urals, as well as by carbonaceous and halogen rocks.

The mineral resources of the Urals are characterized by a great variety. This is where we find the iron-ore deposits (Kusin, Vysokogorks, Baikal), chromite

(Saranovsk, Kimpersai, Don), silicate and nickel (Khalilovo), copper ore (Gai, Sibai), and bauxite deposits (Northern and Southern Ural bauxite-bearing regions). Chrysotile-asbestos (Bazhenov, Dzhetygarinsk) and talc (Shabrov) deposits are related to the serpentinites of the Urals. The deposits of magnetite (Satka, Beloretsk), manufacturing and precious stones are also developed. Coal-bearing basins and deposits are known to be situated in the Urals (Kizel, Chelyabinsk).

The Epi-Paleozoic platforms (West Siberian, Turan, and Scythian) have a distinct two-stage structure. The Hercynian basement is deposited at the depths from 2-3 to 10 km. The platform mantle is composed of terrigenous-calcareous, terrigenous-ferrugenous, glauconitic, siliceous, marly, and saline formations. The most important mineral resources in the platform mantle are oil, gas, and coal. Deposits of iron and manganese ores as well as bauxites are widely spread. A large number of rocks can function as building materials.

A highly significant structural element of the Scythian plate is the Donetsk folded system, which penetrates into the East-European platform at a considerable depth. The Donetsk basin represents a system of anticlines and synclines accompanied by numerous ruptures. The basin is composed of rocks of all systems ranging from those of the Devonian to Quaternary periods. The thickest Carboniferous deposits are found to be coal-bearing.

Regions of Mesozoic Folding

The mesozoids of the USSR include the Verkhoyansk-Chukotka, Mongol-Okhotsk, and Sikhote-Alin folded regions in the northeast and east of this country. Within the confines of *the Verkhoyansk-Chukotka region* there are anticlinal (Verkhoyansk, Yana-Kolyma) and synclinal zones, as well as Pre-Cambrian median massifs. Intermontane depressions (Onotsk, Zyryanovo) have been established and deep faults have been traced.

Geosynclinal complexes (Middle Carboniferous and Middle Jurassic) and orogenic (Upper Jurassic and Lower Cretaceous) can be singled out in the structure of this region. The former consists predominantly of terrigenous rocks of equal composition, e. g. sandstones and clay rocks (with the thickness of up to 10 km). The orogenic complex is constituted by continental coal-bearing and volcanic rocks. The Cis-Verkhoyansk foredeep is made up of a thick mass of carboniferous Upper-Jurassic and Lower Cretaceous deposits, which are crumpled into linear folds in the internal zone, while in the external zone they are deposited almost horizontally.

The Sikhote-Alin folded region consists of a number of large structures: Sikhote-Alin anticlinorium, Tetyukha synclinorium, and Khankai median massif. The geosynclinal complex is characterized by an extensive spread of volcanogenic and siliceous masses of Middle and Upper Paleozoic and Mesozoic periods. The orogenic complex is composed of clastic and volcanogenic rocks and is characterized by an intense granitoid intrusions.

The median massifs of Kolyma, Omolon, Okhotsk, Burein and others constitute an important characteristic of tectonic structure of the territory of Mesozoic folding, because it covers a considerable territory. In the most

typical case these areas of Pre-Cambrian and Early Paleozoic consolidation consist of the basement and the platform mantle. The former consists of gneisses, and amphibolites, gabbroids, and granitoids connected with them. The mantle is represented by terrigenous and carbonaceous, slightly dislocated deposits of marked thickness.

The marginal volcanic belt passes along the edge of the consolidated continent, separating the above-mentioned regions of Mesozoic folding from marginal seas. The rocks belonging to the Cretaceous, Paleogene, Neogene, and Quaternary systems participate in the structure of the belt. They are represented by lavas, tuffs, and intrusive formations of acid and medium composition. In the troughs and depressions of the belt there can be found continental carboniferous and marine sedimentary deposits. Along the line of faults intrusive bodies of granitoid composition are situated.

Within the boundaries of the regions of Mesozoic folding various deposits of mineral resources have been discovered. Among them there are ore deposits connected with geosynclinal and orogenic complexes, and caustobioliths are with platform ones. In particular, deposits of tin, tungsten, antimony, mercury, bismuth, and polymetals have been found. There are also basins and deposits of hard (Lena and Zyryanovo basins and Sangar deposit) and brown (Kangalas, Uglovsk, Artyemovsk deposits) coals.

Regions of Cenozoic Folding

Regions of Cenozoic folding belong to two different zones in diverse geosynclinal belts and are thus markedly distinct according to their geological development and structure. The regions of Mesozoic folding of *the Mediterranean belt* are found in the orogenic stage of development throughout their extension. In the folded structures of *the Pacific belt* the geosynclinal stage of development has been in the state of progress up till now, though some parts of the territory have already reached the orogenic stage. All the way from this zone we can trace contemporary geosynclinal troughs, which are connected with deep-water trenches, active volcanism, and deep-focus earthquakes.

The Caucasus is the most typical Alpine folded structure characterized by a wide development of structural and formation zones. Within the boundaries of the Caucasian folded system we have the meganticlinorium of the Great and Minor Caucasus; the Terek-Caspian and Indol-Kuban foredeeps brought together into the Ciscaucasian foredeep; the intermontane depressions of Rioni and Kura; the Transcaucasian and North-Caucasian deep faults, the Pshekish-Tyrnyauz sutural zone, and others.

The meganticlinorium of the Great Caucasus is formed by the echelon-like arranged anticlinoria and synclinoria that alternate with each other. The Ciscaucasian foredeep is situated along the northern wall of the Great Caucasus meganticlinorium, while the Rioni and the Kura intermontane depressions occur along its southern wall. Anticlinoria and synclinoria are also distinguished in the meganticlinorium of the Minor Caucasus. The thickness of the earth's crust in the district of the Great Caucasus is 60 km. Within the area of Minor Caucasus it is 45 km.

The folded structure of the Great Caucasus was formed by geosynclinal complexes of Paleozoic, Mesozoic, and Paleogene of different age or the complexes that were dislocated as a result of numerous faults and outburst by non-coetaneous intrusions. The geosynclinal complex is composed of sandy-clay and carbonate rocks of Jurassic, Cretaceous, and Paleogene which gently and monoclinaly occur in the northern wall of the meganticlinorium, and in the southern wall they are steep and crumpled into folds complicated by overthrusts. In the geological structure of the Minor Caucasus the principal role is attributed to the sedimentary and volcanogenic formations of Jurassic, Cretaceous, and Paleogene.

The mineral resources of the Caucasus are referred to the groups of ores and caustobiolisths. Within the confines of the Great Caucasus there are lead and zinc (Sadon), tungsten-molybdenum (Tyrnyauz), and copper-ore (Urup) deposits. Iron-ore (Dashkesan) and manganese (Chiatura) deposits are also known. In the Caucasus hard coal is correlated with Jurassic (Tkibuli, Tkvarcheli) and carboniferous (Labinsk) deposits. The deposits of oil are associated with Meso- and Cenozoic deposits of foredeeps and intermontane areas. Tuffs, andesites, and granites are regarded as building materials.

The folded Cenozoic regions of the Pacific belt are found to be in various stages of geosynclinal development and have different types of structures. This is where positive (geosynclinal) structures and negative (deep-water basins, e. g. Bering Sea and South Kuril varieties) are distinguished, together with the oceanic trenches, which do not have any granitic layer in the earth's crust section. The greater part of the area is the region of contemporary sedimentation, which is characterized by a high degree of seismicity and intense volcanism (Kamchatka, Kuril Islands). In the geological structure the thick sedimentary and volcanogenic sedimentary masses of Cretaceous, Paleogene, and Neogene of Quaternary systems play the main role, combined into the system of folded structures. The more ancient ones are the metamorphic rocks of Paleozoic and Mesozoic (Kamchatka), and Upper Cretaceous sandy-clay deposits (Kuril Islands).

The Sakhalin region is characterized by the exposures of Cretaceous, Paleogene, and Neogene deposits. In the south-eastern part of the island the outcrops of Paleozoic and Mesozoic rocks give rise to the East Sakhalin elevation. On the western coast the West Sakhalin trough is distinguished. These structural elements are divided by the Central Sakhalin graben, which is filled with Neogene-Quaternary deposits. The North Sakhalin trough covers the southern part of the island.

Among the mineral resources of the Cenozoic folding of the Pacific belt oil, fuel gas (Sakhalin), and coal (Sakhalin, Kamchatka-Koryak region) are of industrial importance. Ore minerals are represented by the deposits of mercury and antimony, copper, zinc, and nickel ores. Volcanogenic deposits of native sulphur can be found here. Thermal waters (Kamchatka) also present a certain interest.

Chapter 20 Geotectonic Hypotheses

The problem concerning the development of the Earth and the earth's crust, as well as factors conditioning the tectonic movements, which have the predominant role in this development, proves to be very complicated and debatable. For two centuries within which geology has been progressing as science, a large number of hypotheses of geotectonic development have been advanced. However, not one of them has covered all aspects of the development of the earth's crust. To a certain extent, each hypothesis corresponded to the level of knowledge of its time, but with the accumulation of the new factual data on the Earth's geology was, as a rule, almost wholly rejected.

The plethora of geotectonic hypotheses and their relatively ephemeral character can be explained by our insufficient knowledge of the Earth. For instance, too little is known about the impact of cosmic energy on the tectonic processes. There does not exist any reliable information on the thermodynamic conditions and the composition of matter in the interior zones of the planet. The ocean floor has been studied but poorly.

The fact that all these problems and many others have not been solved makes it impossible at present to create in its accomplished form a unique and harmonious theory concerning the development of the Earth, as well as the formation and evolution of the earth's crust. Even the most up-to-date concepts are not deprived of serious deficiencies, though many facts are in no way contradictory.

All the geotectonic hypotheses that have been elaborated up till now, and that are related to the formation of the earth's crust and its various types have been treating the subjects in question from the viewpoints of either fixism or mobilism. *Fixism* attributes the main role in the formation of the earth's crust structures to vertical tectonic movements. The established horizontal displacements are considered to be the variables of vertical movements. According to this approach there can be changes in the dimensions and forms of continents, though any possibility of the alteration of their spatial position is totally excluded. The movements of abyssal mantle substance are characterized by a radial direction and are either thermogravitational or gravitational.

The mobolistic hypotheses allot the principal importance in the formation of the earth's crust and geological structure to the horizontal displacement of blocks of continents and the ocean floor; vertical displacements are regarded as the variables of the horizontal ones. It is considered that the convection heat flows of the mantle substance, which set these blocks into motion, move in the asthenosphere in closed orbits: ascending under the mid-oceanic ridges or descending under the deep-water trenches of oceanic basins.

Fixism Hypotheses

The contraction hypothesis was elaborated by L. Elie de Beaumont, E. Suess, G. Haug, H. Stille, A. Karpinsky, and I. Mushketov on the basis of the cosmogenic Kant-Laplace hypothesis, that the Solar System originated from an

overheated nebula. According to this hypothesis the originally overheated Earth was slowly cooled with the decrease of volume. It is assumed that the cooling process is now in progress at great depths.

This results in that the earth's crust lags behind, as it were, from the inner parts of the planet in their process of contraction and reduction in volume. As the interior volume decreases, the crust is deformed, i. e. undergoes crumpling and fracturing. According to the hypothesis the zones of crumpling correspond to the zones of folding, while along the large ruptures there takes place the subsidence of blocks and the formation of oceanic basins.

What served to prove the decrease of the Earth's interior volume were the data on the crumpling of beds in contemporary mountain structures. The substantial decrease of the Earth's volume in the process of cooling has not been substantiated in terms of physics. However, following the hypothesis of the Earth's 'cold' origin, one should not expect to find the decrease of the volume within the subsequent heating of the planet on such a wide scale.

Proponents of contraction hypothesis attach maximum attention to tangential deformations of the earth's crust. Within the framework of the said hypothesis only the mechanism of the crust contraction is shown. The processes of stretching and rifting, as well as the essential differences in the structure and thickness of continental and oceanic varieties of the crust are left without any explanation. The same can be said of the question why folding was actively manifested within the parts of the thick continental crust rather than in the thin oceanic one. No explanation of the periodicity of the epochs of folding takes place. At the same time, the main merit of the contraction hypothesis consists in the elaboration of the scientific study of geosynclines, as well as the orogenic and platform stages in the development of the earth's crust.

On the contemporary level the ideas of the contraction hypothesis have found their reflection in neocontractionism. On Earth as with other planets of the Solar system the overall cooling process takes place as well as the contraction that is inevitable under these circumstances. Contraction, which has been part and parcel of the development of our planet, can inevitably leave a mark on geotectonic processes. The incessant loss of thermal energy and the unavoidable contraction have been one of the most important and directed processes within all the 4.6-5 bln years that our planet exists.

According to present-day data there is a possibility for the processes involving the compression of the lithosphere to be manifested under the action of contraction forces, though on a somewhat different scale than that specified by the contraction hypothesis. The estimates show that the reduction of the Earth's radius reaches 4.5 cm in a century.

The hypothesis of the expanding Earth (M. Read, B. Lindeman, M. Tetyaev, I. Kirillov, L. Edied, and W. Carry) presupposes that the main planetary type of deformations was extension (stretching), and not compression, as it was explained by the contraction hypothesis. In compliance with the hypothesis, in its initial state the Earth had the density of 9.13 g/cm^3, but not 5.52 g/cm^3, while its radius was equal to 5 430 km (6 371 km in its current value). Besides, the whole surface of the planet was covered with a thick crust of the continental type. In accordance with the Dirac principle which is the basis of the hypothesis of the

expanding Earth, the overall decrease in the density of the material was the prerequisite for the Earth to attain its present size. This was accompanied by the ruptures of the crust, the separation of certain fragments which gave rise to the formation of contemporary continents.

According to the hypothesis the surface of the Earth has doubled its size over the past 345 mln years. This kind of considerable increase in the dimensions of the Earth finds no physical substantiation. The hypothesis does not agree with geological data either. Thus, a great increase of the planet had to be accompanied by a marked reduction of speed of its rotation, which could influence the evolution of plants and animals. However, no traces of such changes have been discovered in the history of geological development. The hypothesis provides no explanation of the origin of folding and the periodicity of tectonic processes.

The pulsation hypothesis (W. Bucher, M. Usov, V. Obruchev, and E. Milanovsky) presupposes that in the development of the Earth the periods of expansion alternate with those of compression. According to this hypothesis the phases of the Earth's expansion are characterized by radial and vertical movements. In the mobile belts there is the stretching of the crust and the formation of geosynclines. The latter, which had undergone folding in the preceding phases of compression, are transformed into mountain structures under the influence of forces of isostatic adjustment. In stable places the crust is swelled and broken by the faults into horsts and grabens, accompanied by the formation of volcanoes and the areal eruptions of lavas.

In phases of compression the crust undergoes substantial, tangential and horizontal movements. The sedimentary masses, which fill the geosynclines, are crumpled into folds. During the refusion of rocks in the deep-seated parts of geosynclines there takes place the formation of granites with gneissic structure. The stable places adjacent to the geosynclines undergo folded deformations. In the history of the Earth the evolutionary and revolutionary periods alternate as the regular accumulation of energy takes place. The source of energy can be the gravitational density and radiogenic heat.

The pulsation hypothesis explains a wide scope of tectonic and magmatic phenomena. It well explains the deformations, stretching, and compression, and substantiates the periodicity in the epochs of folding.

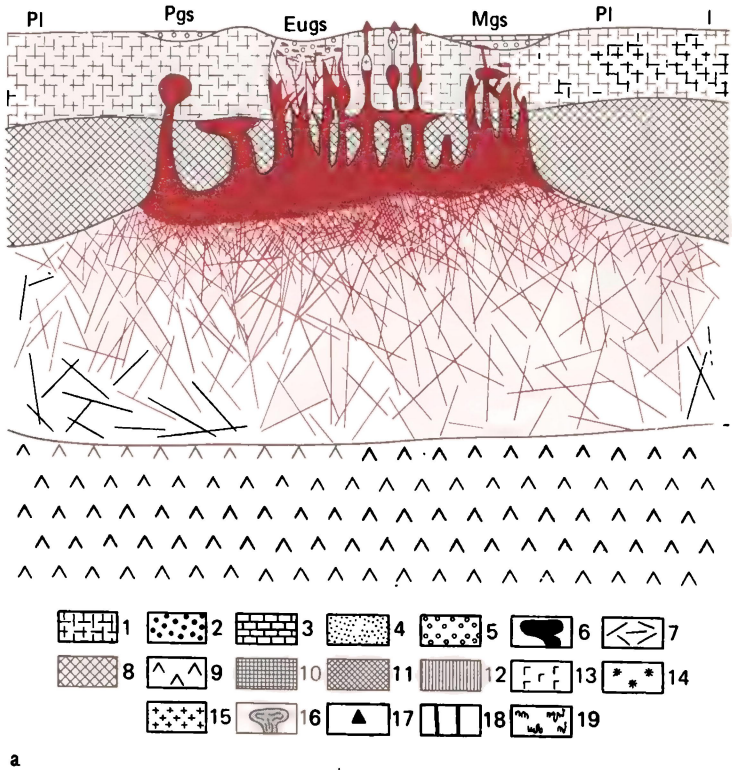
However, the hypothesis does not prove the pulsations in the volume of the Earth and does not explain their abyssal causes, since the reference to the confrontation of attractive and repulsive forces is fairly general.

The pulsation hypothesis cannot explain the whole process of tectogenesis because epochs of general compression or extension of the lithosphere do not exist as such. They are constantly manifested together, which can be seen in the contemporary epoch, e. g. the rifting in oceans, the folding, and overthrust formation in mobile belts along their periphery. The pulsation hypothesis provides no explanation as to the formation of sheet-folded structures. Hence, our knowledge of the pulsation of the Earth's volume can serve only as something that is supplementary to the universal model of tectogenesis. In addition to this, it is more likely that the increase of the Earth's radius is more probable than otherwise.

The abyssal gravitational hypothesis (V. Beloussov, R. van Bemmelen) is related to present-day fixism and consists of the following precepts. It is based on cosmogenic hypothesis of originally cold Earth (O. Shmidt, V. Fesenkov) and the concepts of matter differentiation on the mantle and core boundary due to radioactive heating. Heavy components are added to the core, lighter components are rising up and concentrate in the mantle on the asthenosphere level. The displacement of light substance that moves in channels causes the asthenosphere excitation impulses and its interaction with lithosphere takes place.

V. Beloussov lays particular stress on the significance of the permeability of the crust with respect to the ascending basaltic masses melted in the atmosphere. It is essentially the permeability that determines the type of the regime relevant to the earth's crust (Fig. 102). In the case of a dispersed permeability the ascending basalt permeates the lithosphere with a dense network of channels. The ultrabasic magma, which penetrates together with basalt, gives rise to the alteration of composition – or the 'basification' of the crust, its heaviness and subsidence (Fig. 102*a*). This stage corresponds to the geosynclinal regime. There

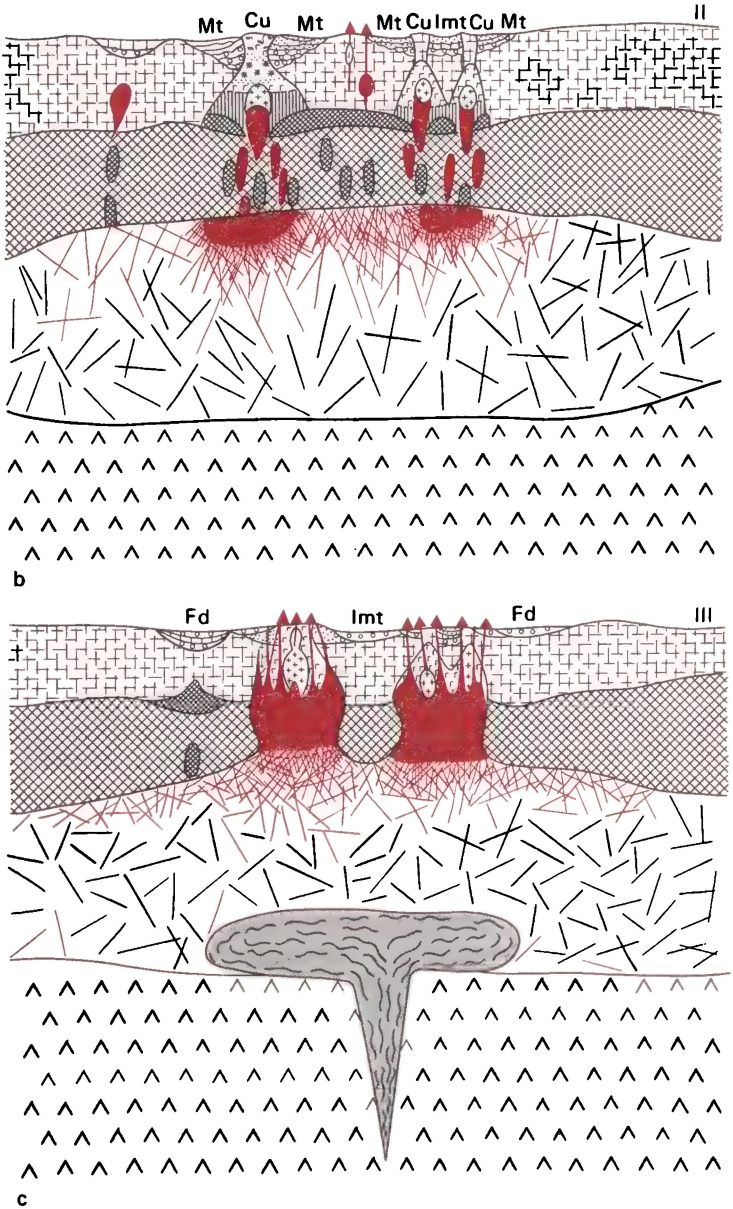
FIGURE 102. The development of the earth's crust, according to V. Beloussov's hypothesis



a

takes place closure of most of the previously existing channels and the formation of 'concentrated' permeability connected with individual systems of deep faults.

Diapir intrusions cause differentiated vertical displacements of individual blocks. The accumulation of subcrustal heat and physicochemical processes become responsible for the metamorphism of the crust, which leads to its



granitization and 'lightening'. The given conditions are correlated with the orogenic regime, when the ascending movements predominate over the descending ones (Fig. 102*b*). The cooling of the intruding masses accompanied by intense denudation leads to the stabilization of the crust, the levelling out of its relief, and the transition to the platform regime (Fig. 102*c*).

The setting of platform regime is associated with a quiet, i.e. slightly heated state of atmosphere. The cooling of the intruded masses accompanied by intense denudation leads to the stabilization of the crust and the levelling out of its relief. The periodicity of the folding stages is conditioned by the intermittent periodic character pertinent to the melting of liquid components from the mantle.

The formation of oceans is connected with the 'basification' of continental lithosphere without its separation. This kind of basification is explained by a particularly intense basaltic volcanism, which resulted in that the contemporary oceans originated in the end of the Paleozoic and Early Mesozoic periods.

In general V. Beloussov's hypothesis explains practically the whole variety of characteristic features that are relevant to the development of lithosphere under different geotectonic regimes only as far as vertical movements are concerned. Folding and overthrusts are considered to be secondary processes. The principles of hypothesis that still call for discussion are: the absence of any interpretation of the nature and mechanism of horizontal displacements under observation; the insufficiently authentic treatment of processes related to the basification of continental crust and the origin of oceans.

The mechanism of the deep-seated differentiation of mantle substance has so far been inadequately studied, though a large number of scientists continue to devote to it their ever-growing attention. Thus, in R. van Bemmelen's hypothesis the geotectonic processes are reduced to those involving the separation of mantle substance on three levels - the lower mantle, the upper mantle (asthenosphere), and the crust. In this hypothesis, which is called undation, it can be assumed that there is a horizontal displacement of blocks of lithosphere as a result of magaundation, or the thinning of lower mantle and increase of its volume. This is accompanied by rupture and sliding of blocks of lithosphere along the slopes and layers of substance from the deeper regions of the upper mantle become exposed in the ruptures. In the upper mantle there is a manifestation of geoundation, or processes that pertain to the heating and melting of basalt, and that lead to the upwarping, sliding, and crumpling of geosynclinal sediments. The inner part of the crust is characterized by the manifestation of medoundation, i.e. processes connected with the cooling and crystallization of intruding basaltic magma, which lead to the increase in the density of the crust and its subsidence. Thus, it can be said that van Bemmelen's hypothesis synthesizes the ideas of both fixism and mobilism. It acknowledges the gaping fault as the factor conditioning the origin of oceans and horizontal displacement of blocks of lithosphere is assumed to be the manifestation of gravitational forces.

Mobilistic Hypotheses

The hypothesis of horizontal displacement (drift) of continents was formulated by the German geophysicist A. Wegener (1912), who implemented ideas of the

American scientist F. Taylor. In accordance with this hypothesis the granitic (sialic) layer of the earth's crust evenly covered the Earth in the early stages and floated on the basaltic (simatic) layer. Under the action of centrifugal and tidal forces the granitic layer was brought together into a single great super continent Pangaea. Since the end of the Paleozoic period and under the influence of exactly the same forces it had begun to split into separate large blocks, or continents, which started to float away from each other in the latitudinal direction. The North and South America tore away from Europe and Africa and moved westwards. In the interval between them there emerged the Atlantic Ocean. In their movement South America and Africa underwent a clockwise turning (Fig. 103).

The movement of Hindustan to the northeast, the Antarctic continent to the south, and Australia towards the southeast gave rise to the Indian Ocean that appeared between them. Thus, according to A. Wegener's hypothesis it is Pacific Ocean that is primary, and Atlantic and Indian Oceans are secondary. The formation of folded belts found its explanation in the compression into folds of continents, which experienced the resistance of the underlying basaltic layer in the course of movement.

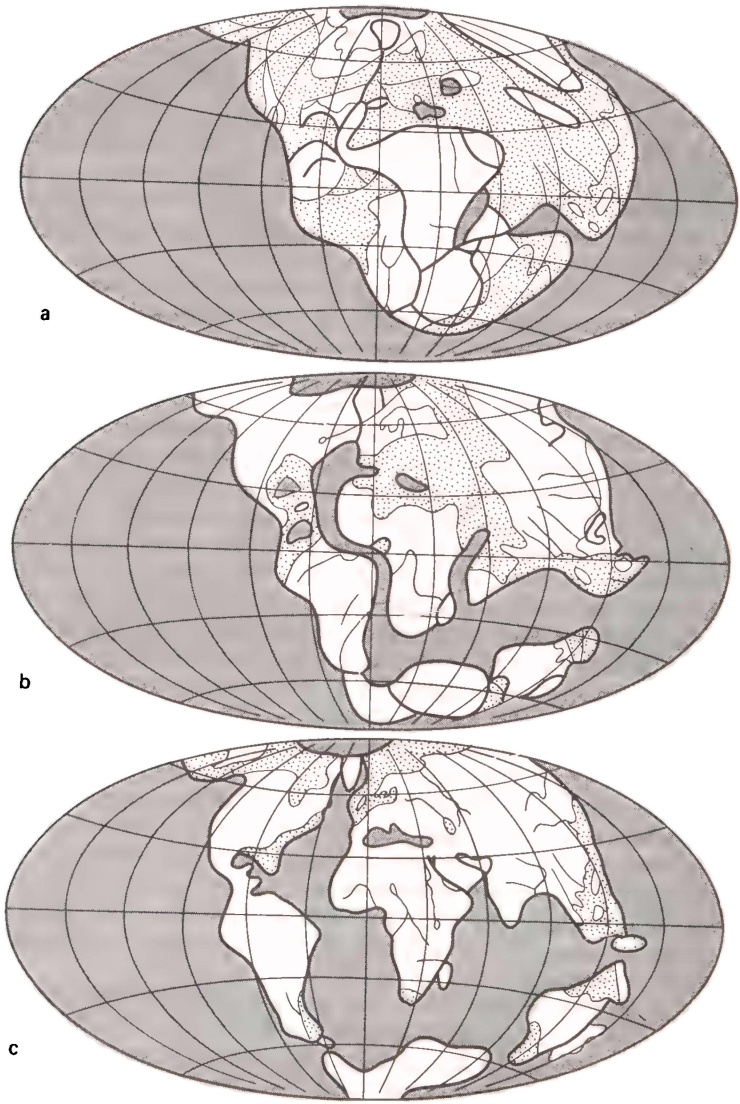
The hypothesis was based on the similarity of the contours of continents, their geological structure, the animal and plant world. However, it had an unsatisfactory physical grounding since it could not provide any explanation as to the causes and mechanism pertaining to the movement of solid continents along the rigid solid substrate. The vertical tectonic movements and deep-focus earthquakes had not been interpreted; the interrelationship between the crust and the mantle was ignored. For some time, the hypothesis was popular, but was later rejected as it could not be proved to be scientifically valid.

The scientific study of paleomagnetism and the investigation of the ocean floor which resulted in the discovery of the world system of mid-oceanic ridges with their axial rifts, the subsequent data concerning the fundamental difference between the oceanic and continental types of crust, the finding of a considerable thinning of the sedimentary layer towards the median ridges and the increasing of heat flow in the axial zone of the latter, and, lastly, the establishing of asthenosphere in the mantle – all this has led to the formation of the ideas of mobilism on an absolutely new basis.

The concept of new global tectonics (B. Isacks, J. Oliver, L. Sikes) or *plate tectonics* (C. Le Pichon, V. Morgan), which was formulated in the sixties, represents the theoretical generalization of new facts. It is based on the summary of current mobilistic hypotheses pertaining to the spreading of the ocean floor (H. Hess, R. Deitz, and others), transform faults, subduction in the zones of deep-water trenches (Wadati, H. Benioff) and the drift of continents. The ideas of mobilism, the plate tectonics in particular, were supported and developed by the Soviet scientists A. Peive, V. Khain, A. Mikhailov, P. Kropotkin, M. Zonenshain and others.

The basic principles of this new concept consist in the following. The earth's crust and the upper part of the mantle, which form the upper hard sphere – the lithosphere, are underlain by the atmosphere, or the less viscous and more plastic sphere. The lithosphere is divided into relatively small (6-8) number of large hard

FIGURE 103. The movements of continents (according to A. Wegener's hypothesis): *a* – the situation 300 mln years ago; *b* – the situation 80 mln years ago; *c* – the situation one mln year ago



monolithic plates, along the borders of which practically the whole of tectonic and seismic activity is concentrated (Fig. 104).

The lithospheric plates undergo three types of displacement. Spreading takes place in the rift zones of mid-oceanic ridges (the so-called boundaries of further development of constructive or divergent varieties). Compression is confined to the zones of Zavaritsky-Benioff – the deep-water trenches of the marginal parts of the ocean along the deep faults (convergent, destructive, or absorbing boundaries). The shift takes place along the transform faults (transform or sliding boundaries).

The relative displacements of lithospheric plates along the surface of the Earth take place in accordance with the laws of spherical geometry. In the zones characterized by the spreading of mid-oceanic ridges new oceanic crust is originated (hence the term 'constructive boundaries'). In the zones of Zavaritsky-Benioff it is absorbed in the mantle (destructive, absorbed boundaries). This process is called *subduction.* It is assumed that subduction serves to completely compensate for spreading, for which reason the Earth's volume remains constant (Fig. 105).

The factor conditioning the relative displacements of lithospheric plates is said to be *the thermal convection* in the mantle. The rifts of mid-oceanic ridges are situated above the ascending branches of convective cells. The zones of Zavaritsky-Benioff are found to coincide with the descending branches. The oceanic lithosphere moves from the rifts towards these zones, carried off in a conveyer-like manner by horizontal sections of convective cells. The velocity of convection currents varies from 1-3 cm per year. In the earth's crust these vertical and horizontal currents in the closed cells cause tectonic movements in the form of elevations and subsidences, compression and stretching. They lead to the displacement of continental plates or some of their parts.

The displacement of material takes place in the form of a system of closed circles. Geosynclines emerge in the zones where two branches of descending currents are connected, while elevations are typical of those plates in which there is a divergence of uprising currents. Warping is accompanied by compression while elevation goes together with extension and the formation of faults in different directions (this is how mid-oceanic ridges are formed). Oceanic troughs are associated with the descending or horizontal branches of convection currents. Folding is the consequence of the compression of the geosyncline by two neighbouring platforms, during which the plastic material is extruded with the formation of mountains, or as a result of the impact of continental and oceanic lithospheric plates.

The concept that has been expounded above is thus distinguished by its relative simplicity, logical construction, and accomplishment. Its merit consists in the mathematical formalization of plate kinematics, which made it possible to employ computers in reconstructing the position of continents and the paleodepths of the ocean. The hypothesis is known to possess the power of prediction since on its basis the age of the whole series of magnetic anomalies of the ocean has been evaluated. This was confirmed by the deep-water drilling and the study of sections of deposits on the continent.

Neomobilism emerged on the basis of absolutely new factual material, which

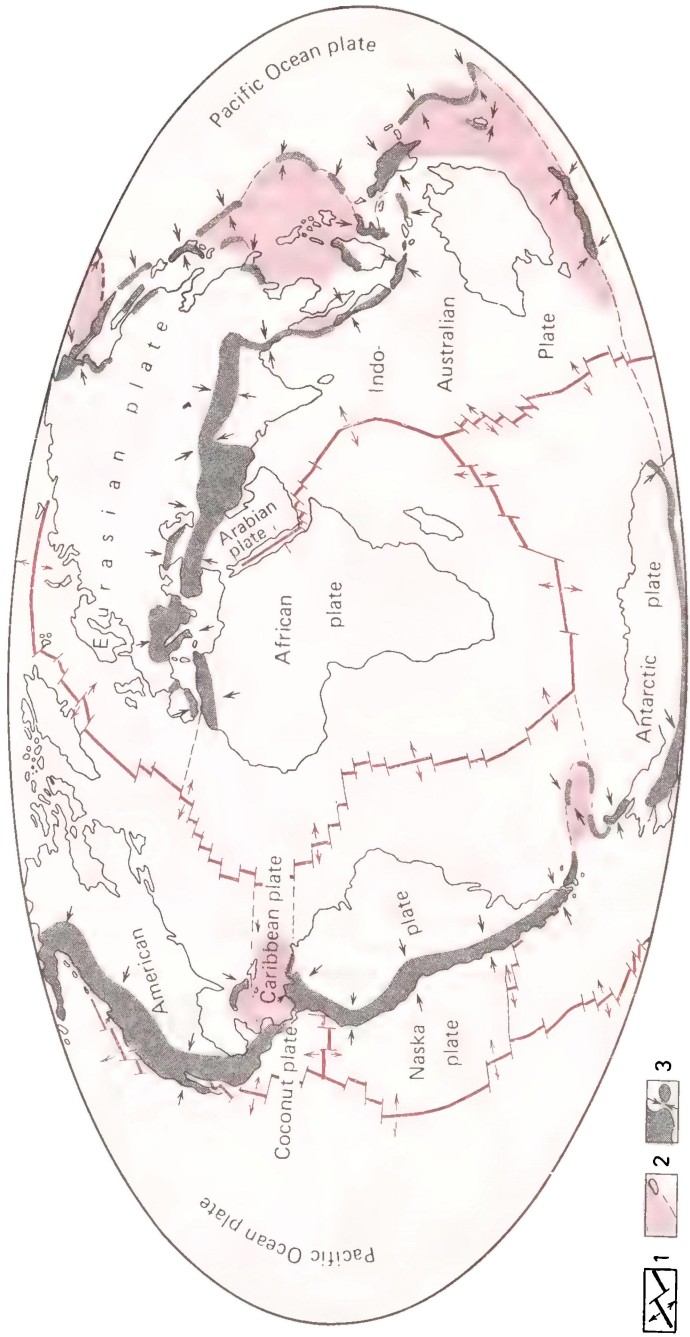


FIGURE 104. **A schematic drawing of lithospheric plates:**
1 - mid-oceanic ridges with transform faults; *2* contemporary orthogeosynclines;
3 – Alpine orogenic belts and island arcs

was received with the help of new technical means – deep-water drilling and observations carried out from submarines. It can thus be considered that neomobilism is the product of the most recent scientific and technical revolution.

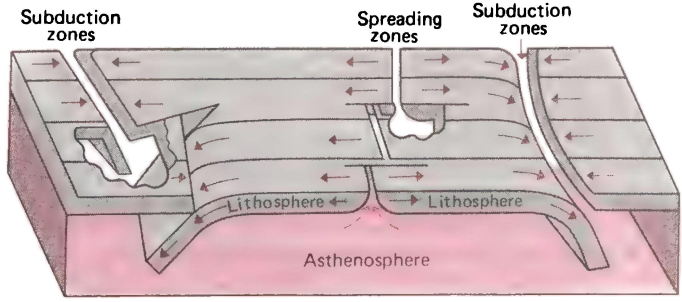
The hypothesis of plate tectonics is not devoid of complex and inadequately elaborated problems. Insufficient attention has been given to physicochemical parameters and the position of asthenosphere in space. The question concerning the number of lithospheric plates has remained unsolved. The same can be said about the existence of the so-called 'microplates'. The assumption concerning the absolute hardness and elasticity of lithospheric plates does not wholly correspond to the actual state of things. Within the framework of plate tectonics the problem of interplate tectonic and magmatic activity has not received any solution.

Of three basic types of reciprocal displacements of plates two are at present most convincingly proved, viz. spreading according to the data provided by drilling and the observations made from submarines, and the displacements along transform faults as studied by means of observations made from submarines. However, the process of spreading, the structure and character of displacements along the transform faults have been discovered to be more complicated than it was first imagined by the proponents of plate tectonics hypothesis. There is also a sufficient amount of proof in favour of subduction.

The data of paleomagnetism and paleokinematic reconstructions have consolidated the assumption regarding the constancy of the Earth's volume, which rests upon the compensation of subduction for spreading. A special problem is presented by the mechanism related to the dislocation of lithospheric plates. In its initial variant, the concept of plate tectonics presupposed the thermal convection in the upper mantle to be the driving force. At present it has been proved that convection is not purely thermal, that it covers the whole mantle, and probably is of two-stage character.

The hypothesis cannot explain the inherited factors pertinent to the development of large structures of continents in the course of many geological periods. The continuous non-deformed subsidence of the coasts of Atlantic Ocean does not correspond to this hypothesis, where one would conversely expect to find subductions and formations of marginal mountain chains. No satisfactory

FIGURE 105. A block-diagram of the lithospheric movement plates



explanation has as yet been given concerning the development of platforms and the formation of epiplatform orogenic belts.

The search for alternative and compromise concepts has been carried out along different lines and at a different degree of acknowledgment of certain precepts of plate tectonics. As far as E. Artyushkov (1979) is concerned, the same kinematic pattern of the reciprocal dislocations of lithospheric plates as in plate tectonics is given, but the mechanism, as suggested by him, is quite different. It is considered that convection currents in the mantle cannot involve into their movement the plates of lithosphere since the viscosity of the asthenosphere is markedly low. The accumulation of mantle material with an abnormally low degree of density in the sole of the crust results in the formation of elevations, the disruption of gravitational equilibrium and the spread of crust and mantle with the emergence of considerable horizontal displacements. Under the influence of this process and along the mid-oceanic ridges, there takes place the rupture of the crust and the intrusion of anomalous mantle with the displacement of plates of oceanic lithosphere sideways.

The platform elevations (shields) emerge above the 'traps' for the anomalous mantle. If these 'traps' are close to the ascending current of mantle material, high mountain structures are formed. If the 'traps' are at a remote distance from this kind of current, the mantle cools, the lithosphere thickens, its sole subsides, and a sedimentary basin of the syneclise type is formed.

E. Artyushkov's model regards new factors of tectogenesis, i.e. horizontal stresses, connected with the formation of elevations and phase transformations under the troughs. The hypothesis presents a combination of deep-seated differentiation and the uplift of its products from the basement of the mantle with horizontal movements on the level of asthenosphere and lithosphere.

A. Peive's (1982) mobilistic concepts of tectogenesis is grounded on the following principles. The development of lithosphere is determined by the differentiation of mantle matter. Its consequence is the preponderance of ascending thermal mass currents and the lack of large closed convective cells (as distinct from plate tectonics). In the proximity of the planet's surface the ascending mass currents are transformed into lateral ones (as in E. Artyushkov's model). Bringing out the absence of a continuous asthenospheric layer (and, consequently, a clear-cut boundary of the lithosphere), the authors consider lithospheric plates as elastically viscous rather than elastic, as in the plate tectonics. Lamination of plates and structural disharmony between individual layers are brought into light.

The authors of the said concept lay particular stress on the fact that tectonic activity of the lithosphere follows the energetic activity of the mantle and undergoes periodic changes. The model presupposes the uplift of asthenosphere, the rupture of oceanic crust, the melting of new crust and its transformation into that of continental variety, the new rise of heated mantle, the new formations of oceanic crust and its thrust (obduction) upon the continental one along the periphery of the ocean. Subduction is recognized, though on a limited scale. The concept considers the dislocation of lithospheric plates on the basis of hydrodynamics, which is more appropriate than in the case of plate tectonics.

Other Geotectonic Hypotheses and Concepts

There is not a single contemporary hypothesis pertaining to the formation and development of the earth's crust that finds general recognition. This is primarily accounted for by the inadequacy of our knowledge of the structure of the upper mantle, the lower parts of the earth's crust, and the early stages of its formation.

The geosynclinal hypothesis proves to be a remarkable generalization of all the data on the geology of continents. However, developed on the analysis of intercontinental tectonics and magmatism, it was found to be incapable to explain the fundamental features of the structure and development of the oceanic earth's crust.

Plate tectonics, though providing a logical and consistent interpretation of the main features of the formation of oceanic crust, does not give any due consideration to the intercontinental dislocations and magmatism, and is weakly connected with the problems of intercontinental minerageny.

One of the principal prerequisites of contemporary mobilism is the concept of overall global propagation of the asthenospheric layer, along which the movement of lithospheric plates takes place. However, at present it is known that this particular layer does not find a clear-cut expression everywhere. It is most distinctly registered in the regions of the transition from the ocean to the continent, in those parts of the territory that are characterized by orogenic activization and riftogenesis, as well as young folding. At the same time over the vast spaces of stable cratons it is by far not always that the asthenospheric layer lends itself to be discovered.

Hence, when emphasizing the great role of horizontal tectonic movements, it is necessary to take into consideration, in the light of data referring to the discontinuities of asthenospheric layer, that the drift of enormous lithospheric plates, which includes whole continents, is made more difficult. There is some probability that in different epochs of tectogenesis the asthenosphere received a kind of impulse to resume its active functioning in various regions of the world due to the arrangement of mobile belts within each period. In connection with the fact that in the course of geological history the situation of mobile belts underwent numerous changes, it may well be assumed that almost all the parts of the earth's crust could have been subjected to these displacements at one time or another.

In A. Mikhailov's opinion (1986) the concepts associated with the continental crust are quite tenable for the period of geological history, beginning with the Late Proterozoic age (1.65 bln years), when the continental crust was being formed in accordance with the main precepts of the geosynclinal hypothesis. As far as the oceanic crust is concerned, it is possible to adduce data on plate tectonics only since the Jurassic period (170-160 mln years). Earlier stages in the history of the development of the earth's crust still remain suppositions alone.

As can be inferred from the concepts discussed above even the orthodox ones cannot furnish any consistent interpretation of the basic regularities pertinent to the development and structure of the earth's crust. What proves to be an apposite solution to the problem is the acknowledgment of vertical, as well as horizontal movements, and, consequently, the accounting of the particular principles of

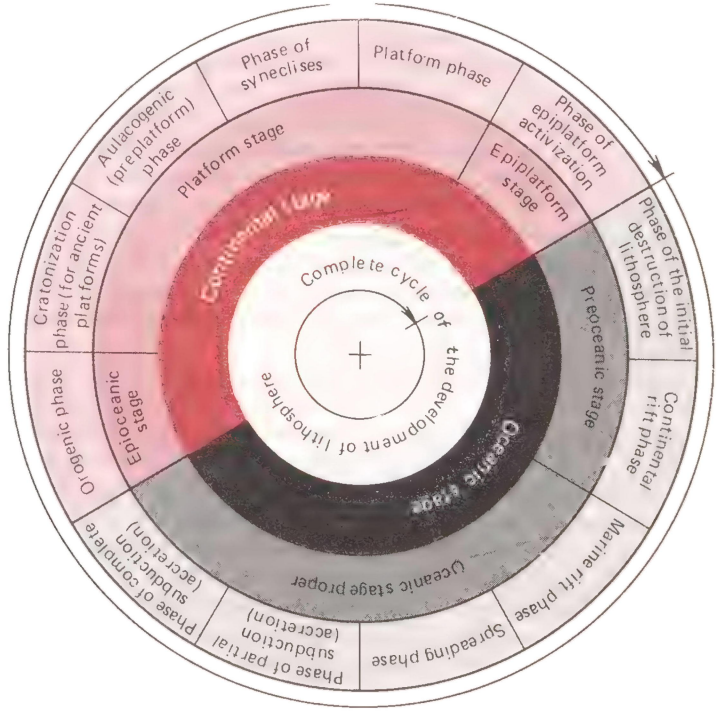
contemporary fixism and mobilism. The new ideas concerning the phasal character of the development of lithosphere in the process of evolution through oceanic and continental stages have recently been evolved. A number of scientists associate these new ideas with the traditional scientific study of geosynclines and platforms, regarding the former and the latter as particular stages in the development of oceans and continents.

According to V. Gavrilov (1986), the complete cycle in the development of lithosphere of a certain region of the world consists of two phases – oceanic genesis and continental genesis (Fig. 106).

Ocean genesis, which includes the pre-oceanic stage and oceanic stage proper, is a process involving the fracturing and destruction of the earlier existing earth's crust (usually of the continental type) at the expense of riftogenesis and the formation of new crust of the oceanic type by means of spreading.

The pre-oceanic stage begins on the continents. The uplift of the heated mantle substance leads to the bending and cracking of lithosphere and the formation of faults along which the basic and ultrabasic magma penetrates into the earth's crust and on the surface (the phase of initial destruction). This is followed by the formation of rifts that are brought together into systems. In the oceanic stage proper there takes place the manifestation of oceans. Processes of spreading, which result in the widening of the sea area, become apparent. Subduction and

FIGURE 106. **A complete cycle of the lithospheric development**



obduction give rise to the formation of mountain-folded structures. It is precisely these phases of oceanic genesis that correspond to the geosynclinal process in the way it is traditionally understood. This results in the formation of continental crust at the expense of the reworking of sedimentary and volcanogenic masses, their regional metamorphism and magmatism.

Continental genesis is a process of consolidation and accretion of the thickness of continental crust. It comprises three stages: the epioceanic, platform, and the epiplatform ones. The epioceanic stage, which, in traditional terms, corresponds to the orogenic stage of the geosyncline development, is characterized by the further formation and growth of mountain-folded structures. The earth's crust has a typically continental structure and an increased thickness. The intense and comprehensive development of faults determines the horizontal movements which form overthrusts, sheets, and overthrust sheets, and also give rise to contrasting vertical movements of individual blocks of the crust. In the structure of the region there can exist intercontinental sea basins with the oceanic type of crust.

Within the process of peneplanation of the relief the decrease of the tectonic activity becomes transformed into the platform stage of development. The phase of cratonization characteristic of ancient platforms is distinguished by the processes of hemogenization widening and the increase of stability, as well as crystallinity of platform basement. The aulacogene phase is characterized by the primary splitting of the basement of platforms and the deposition of aulacogenes. The phase of syneclises (particularly in the zones of aulacogenes) is remarkable for the vast warping, and the formation of depressions (syneclises), separated by the benches of the basement. The further warping (plate phase) leads to the widening of the area of syneclises and their merging. Next comes the elevation of the platforms and the regression of sea basins. The epiplatform stage finds its expression in epiplatform activization: the platform parts become involved in active processes of the formation of mountains. Arched-block structures are formed with a clearly expressed trend towards elevation.

The outline of the evolution of lithosphere as has just been presented cannot possibly be regarded as perfect. Its principal advantages consist in the creation of an overall model of the basic stages in the development of lithosphere, the reciprocal correlation of traditional geosynclinal concepts with the newly elaborated geotectonic ones, the use of formations as applied to the processes of oceanic genesis and tectogenesis.

To sum up, geotectonics has now entered the stage of its development when the decision will rest entirely on the quantitative assessment of the impact of some particular factors, e. g. the thermal regime of the Earth, the physical condition of its abyssal parts, the mechanism of gravitation, differentiation, convection, and others. The geotectonic hypothesis should be based on the whole variety of physical and chemical processes that take place in the Earth, and should treat them in dialectical interrelationship and historical consecutiveness.

Chapter 21 Research Methods and Graphical Modelling of Crustal Structure

The practical engineering activity of people has always taken place either within the confines of large regions, or individual parts of the earth's crust composed of rock complexes that are highly varied as far as their composition, forms of attitude, and factors conditioning their development are concerned. In the process of geological investigations conducted on the basis of the study of geological objects, their interconnections and changes in time and space, the evaluation of relations with environment the models of the parts of the earth's crust are created. They usually represent the description of the geological structure of territories in combination with graphical materials, that serve to give a clear-cut illustration and additional data of the said description. Graphical models of the territory under investigation present an objective reflection of what is now known about the structure, composition, and properties of the earth's surface, as well as of deep-seated parts of the earth's crust that are contiguous to the surface. These graphical models include geological maps, plans, sections, stratigraphic columns, diagrams, etc.

Methods of Receiving Geological Information

General Information on Geological Survey. The principal method of investigating the earth's crust is geological survey, the aim of which is to study the geological structure, mineral resources, and the compilation of the geological map of a particular scale. According to the means employed in conducting geological survey, the latter is known to be of two types, viz. the ground survey and remote sensing. In the case of *ground survey*, natural outcrops of rocks, drilling holes and mine workings are employed. Visual studies are, as a rule, supplemented by geophysical and geochemical observations and measurements.

Remote sensing (probing) consists in analyzing the structure of the surface and deep parts of the Earth from such vehicles as planes, satellites and space stations, functioning in the atmosphere or outer space. The aforesaid methods of geological survey are at present closely interrelated. When investigations are conducted on land the aerial and space photographic survey materials are always practically used. The interpretation of materials that are received with the help of remote sensing is carried out with the field (control) observations taken into account.

Geological survey is conducted according to a particular plan, without leaving out any part of the territory so that in the long run it would be possible to bring together the data on individual regions and get the general idea of the geological structure of the whole territory as well as of large regions. The obligatory condition of geological survey is its *quality*, or authenticity, which is determined by the correspondence of the minute characteristics of geological structure to the scale of survey on maps. According to content the present-day geological survey has acquired *a complex* character.

Scales and Methods of Geological Survey. The specification of geological survey is determined by the given scale of mapping.

The larger the scale of survey the more details it will bring out, and the fuller and more reliable the results will be. The subsequent increase of scale of the already prepared map cannot enhance the degree of specification reflecting the geological structure of the region given by the scale of survey.

In the USSR *small-scale survey* (1 : 1 000 000 ÷ 1 : 500 000) is not conducted at present. Geological maps of these scales are compiled by generalizing the data pertaining to more detailed surveys. *Medium-scale surveys* (1:20 000 ÷ 1:100 000) are carried out throughout the whole territory of the Soviet Union with the aim of studying geological structure and a prognostic evaluation of mineral resources. When surveys on these scales are conducted, geophysical and geochemical investigations are carried out and the interpretation of aerial and space photographs is made. Light mine workings are widely used (ditches, clearings, and small pits), as well as shallow boreholes. *Large-scale surveys* (1 : 50 000 ÷ 1 : 25 000) are carried out everywhere in the USSR. On the whole the operations conducted in this stage may well be correlated with the medium scale survey.

However, they are primarily made in the regions of mining industry and use the data of deep drilling.

According to the methods employed in geological survey it is represented by route, areal, and instrumental types.

The route survey that meets the requirement of small-scale maps is conducted along the directions situated mainly across the strike of rocks or folded complexes. Besides, the routes most necessarily cover the points that are most advantageously exposed. The data that have been received are transferred upon the area situated between the routes.

The aerial survey, which is conducted when the scale of mapping is 1 : 200 000 ÷ 1 : 25 000, is carried out on the basis of a regularly distributed network of observation points, which are expressed by natural and artificial (drilling plotted on maps) exposures. Aerial photography, geophysical and geochemical works are extensively used in this kind of survey.

The instrumental survey is used when it is required to produce detailed mapping (scale 1 : 25 000 and larger). The points are arranged along a regular network, and the position of geological boundaries and objects is plotted on a topographic basis with the aid of instrumental means.

The methods of abyssal and *three-dimensional geological mapping* have recently gained a considerable ground in regional investigations. They are used for the exposure of the geological structure of deep-seated horizons and textures. It is a well-established fact that mapping presupposes the use of materials that have been received as a result of terrestrial observations, drilling, mine workings, as well as geophysical and geochemical data.

Types of Ground Geological Survey. Complex geological survey is characterized by the fact that alongside the mapping of bedrocks, the survey of Quaternary deposits and other special surveys take place. The latter include: structure, geomorphological, hydrogeological, geological engineering, metallogenic, geophysical and some other types of survey.

Structure survey, which is conducted within the enclosed areas, helps to reveal key horizons, which reflect geological structures hidden under a mass of deposits. A variety of structure survey is that of the ancient structural stages (crystalline basement) of platform territories, which is conducted on the basis of deep drilling and geophysical information.

Geomorphological survey is concerned with the study and mapping of denudation and accumulation forms of the relief. It is conducted either together with the geological survey or separately and serves as the basis for the study of Quaternary deposits and the exploration of placer deposits.

The survey and mapping of Quaternary deposits usually accompanies the overall geological survey. Its purpose consists in establishing the origin, age and composition of Quaternary deposits.

Hydrogeological survey, which functions as a constituent of the overall geological survey finds its accomplishment in the compilation of a map depicting the water-bearing feature of the region. In the course of a special hydrogeological survey the number and propagation of water-abundance horizons, their stratigraphic position, wateriness, conditions and degree of mineralization are determined.

The geological engineering survey consists in establishing the physical and mechanical properties of rocks, the assessment of the characteristic features of the relief, the activity of denudation processes that are important for the carrying out of construction engineering works, and the development of the deposits of mineral resources.

Geophysical surveys are based on the study of the parameters of the Earth's physical fields, both the natural and the artificial one. These surveys help to determine the Earth's structure including the mantle and the core, the development of rocks of various composition in area and depth, the most important tectonic structures and other geological objects on the basis of their physical properties distinction.

Remote Sensing. Aero- and cosmic methods are the means pertaining to the geological investigation of the Earth.

The aeromethods represent a complex of methods aimed at studying the Earth's surface, which are brought into effect through visual analysis, photographic survey, geophysical and other instruments. *Aerovisual methods* help to speed up the geological works carried out on land, and integrate the results that have been received during the survey of adjoining regions.

Aerophotographic methods enable the geologists to determine the form, size and position of elements of natural landscape, and on the basis of their interrelationship with the geological structure of the territory, carry out the geological interpretation of stereopairs of aerial photographs with the help of a stereoscope (Fig. 107). Geological interpretation is founded on the use of direct and indirect features. The former comprise expressiveness of geological structures in the relief, as well as geometrical form, size and colour of the images, which characterize the specific features of geological objects and their elements. The indirect features include geomorphological indices, the character of vegetation, the colour and degree of the humidification of soils, water springs, etc.

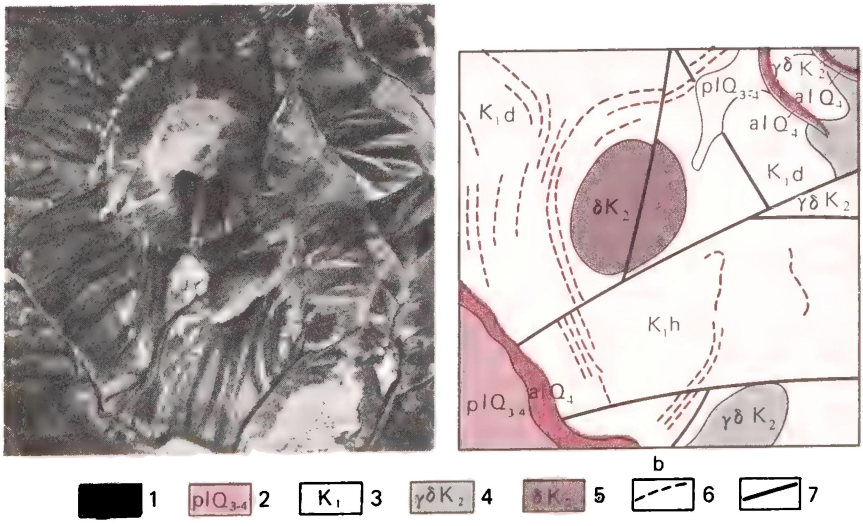
The aerial photographs that are most widely used in aerial photographic survey are those of the black-and-white type. They help to identify up to 35 shades of colour within the black and white extremes. *Colour* and *spectrozonal aerial photographic surveys* have now received a wide range of application too. The fact that they enhance the effect of geological interpretation should be specially brought out. Aerial photographic survey is usually conducted on the scales of 1 : 10 000, 1 : 20 000, 1 : 25 000, 1 : 35 000, 1 : 50 000, 1:100 000, 1:200 000, as well as 1 : 15 000, 1 : 18 000 and 1 : 70 000.

The aerogeophysical methods (aeromagnetic, aeroradiometric, and aerogravi-prospecting varieties) are based on the measurement of natural and artificial physical fields with the help of instruments installed on planes and helicopters. *Radiolocation* and *infra-red air surveys* are considered to be the auxiliary methods of aerial survey.

Cosmic, or *space methods* have opened a new stage in the geological study of the Earth. They are founded on visual observations, the photographing of TV images of the Earth's surface from outer space, as well as on the instrumental recording of various thermal, infra-red, superhigh-frequency, ultraviolet, and other kinds of radiation. The Soviet cosmonaut G. Titov was the first to photograph the Earth from outer space on August 6, 1961.

The space photographs reflecting different landscape conditions of the earth's crust are used for the making of photoplans and, on their interpretation, are employed for the compilation of regional geological maps that are characterized by a high degree of accuracy. Black-and-white, colour or spectrozonal films are used in photography. The scale of image depends on the

FIGURE 107. Medium-scale aerophotograph (a) and the results of its geological interpreting



altitude of survey. At present there is a possibility to receive any scale up to 1 : 100 000 000.

Interpretation is based on the principle of contrast and analogy, the use of geological and geophysical information, and computers. At first the landscape zonation of space photoplan according to phototone or shades of colour characteristic of the images. This is followed by the analysis of the interrelationship of individual components of the landscape with the elements of geological structure, which results in that the space-geological (or tectonic) map of the territory is received.

Faults, saline domes, and other geological structures are more clearly interpreted. Regional and global tectonic structures are established at a considerable depth even when a cover of loose deposits occurs.

Space methods provide every opportunity to receive absolutely new information on ruptured and folded tectonics and the deep structure of the earth's crust. With the help of space representations a large number of important elements pertaining to the deep-seated layers of the earth's crust and the upper mantle have been discovered. They are usually weakly expressed in the structure of the near-surface layers. Boundaries of regions have been specified, and block structures of some of the mountain regions have been established, together with areas favourable for the prospecting of some mineral resources.

In 1979 on the basis of the analysis of data related to the geological interpretation of space photographs that had been received from the 'Meteor' satellites, the space-geological map of linear and ring structures of the USSR territory was compiled. Its scale was 1 : 5 000 000. It proved to be the first of its kind concerned with the direct space-geological mapping of the country on a general scale. This helped to single out the main types of linear and ring structures, their spacial distribution and create the basis for the subsequent tectonic and mineragenic constructions, for the analysis of regional geophysical materials.

Nowadays, the use of space methods has received its further development. What has been compiled includes the space geological map of the USSR (scale 1 : 2 500 000), the map showing ring structures of continents (scale 1:15 000 000), the space tectonic map of the Ukrainian Soviet Socialist Republic (1:1 000 000), those of Vietnam (1 : 1 000 000), Cuba (1 : 500 000) and others. The use of these methods has gained further ground in the study of contemporary and recent geological processes, the exploration of mineral resources and even in prospecting and exploitation of deposits (the location survey of zones of fracture).

Geological Survey of the Floor of Seas and Oceans. When geological operation in water areas are in progress remote sensing is actually employed since any geologist-surveyor, who is aboard a hydrographical vessel, is separated from the sea or ocean floor by a mass of water. For purposes of mapping aerial photographs of shallow-water parts of the shelf are employed. The same can be said of the collection of rock specimens from the sea floor, seismo-acoustic methods, special geophysical methods (marine electric geophysical exploration, magnetic and submarine radiometric survey), under-

water television and photography, the geomorphological method and others.

The research into the deep-seated parts of seas and oceans takes place with the help of submarine hydrographical vessels, special submarines and deep-water instruments, as well as geophysical observations and measurements, equipped with precision technology. The deep-water drilling presents valuable factual material on the structure of the ocean floor.

Geological Map and Other Kinds of Geological Graphing

Types and Kinds of Geological Maps. The geological map, in its general sense, is a graphical representation of the geological structure of a certain part of the earth's crust, continents, or the Earth as a whole, on the topographic or geographic basis with the help of conventional symbols. The geological map shows the extension of outcropping of rocks on the Earth's surface, which are distinguished by their age, origin, composition, and forms of attitude.

The geological map with an explanatory note helps to make statements concerning the formation of the earth's crust and the regularities in the propagation of mineral resources. It serves as the scientific basis for the exploration and prospecting of the deposits of mineral resources and the elaboration of long-term plans of the development of mining industry. Detailed geological maps are of great importance for the design, development, and exploitation of prospected deposits, as well as the planning of mining operations while these are in progress.

Geological maps are constructed on the basis of the geological surveying that has been conducted, theoretical generalization of the achievements in geological sciences and practical experience. In the compilation of geological maps the main role is attributed to such branches of geological science as stratigraphy, geotectonics, structural geology, historical geology, lithology, geochemistry, mineralogy, petrography, geophysics, and the scientific study of the deposits of mineral resources.

The geological map of high quality is the product of complicated creative effort on the part of a body of geologists armed with a profound theoretical knowledge and vast experience in field-work activities. It is the product of an assiduous labour of specialists, who, as a result of their intensive research and analysis, have managed to present the most substantiated and adequately objective interpretation of geological phenomena and facts that were under observation.

According to their content and purpose geological maps are classified as follows: geological maps proper, maps of Quaternary deposits, geomorphological, lithological, tectonic, and hydrogeological maps, maps of mineral resources, and metallogenic (prognostic) maps. What serves as the basis for the making of these maps is the results of the corresponding type of geological survey.

Geological maps proper are essentially stratigraphic maps of Pre-Quaternary bedrocks. They do not show any Quaternary continental deposits with the

exception of those cases when their thickness is considerable or when no information on the bedrocks underlying them is available. The conventional symbols that are used on maps show the age, composition, origin, and the conditions of attitude of rocks, as well as the character of the boundaries that separate them.

Maps of Quaternary deposits show deposits of this kind with their division according to origin, age, and composition. Bedrocks are usually represented as monochromatic entities without any further subdivision. *Lithological maps* illustrate not only the age of rocks, but also their material content.

The tectonic maps show the forms of attitude, the time and conditions pertinent to the formation of structural elements of the earth's crust of different orders. On general tectonic maps the basic structural elements are singled out.

The same can be said of the tectonic regimes and the time the said structural elements were formed.

The regional maps reflect the characteristic features of the structure of definite regions. On tectonic maps structural forms are brought out by means of boundaries or with the help of contours (lines showing the same depths) of the roof or soil of key horizons of unconformity surfaces, and the border lines betwen different complexes.

The geomorphological maps reflect the main types of the relief and its individual elements with their origin and age taken into account. *The hydrogeological maps*, compiled on the geological basis, convey the necessary information on the water-bearing horizons, modes of occurrence, propagation, the composition of origin and the regime of underground waters. *The geological and engineering maps* show the physical and mechanical properties of rocks and the characteristics of contemporary geodynamic phenomena.

The maps of mineral resources are compiled on the geological basis and are meant to convey the data concerning the deposits of mineral resources that are divided into groups the trends of which are utilized for industrial purposes, and according to the scope of their reserves and origin. *Prognostic metallogenic* (generally, mineragenic) *maps* reflect the regularities in the distribution of calcareous deposits of mineral resources and show the more promising fields relevant to various kinds of mineral raw materials.

Depending on the scale of geological maps proper (only those of this type will further be dealt with) they are classified into general, small-, medium-, and large-scale types, as well as the ones of detailed variety.

General maps (scale > 1 : 1 000 000), constructed on the geographical basis, provide the overall representation of the geology of vast territories of countries, continents, and the whole world. *The small-scale maps* (scales 1 : 1 000 000 and 1 : 500 000) are made on a simplified topographic basis and characterize the geological structure of large regions, or countries as such.

The medium-scale maps (scale 1 : 200 000 and 1 : 100 000) are compiled on the exact topographical basis on a rarefied network of structure contours. They convey the information on the main geological features of the territory.

The large-scale maps (scale 1 : 50 000 and 1 : 25 000) are constructed on the exact topographic basis and provide a fairly adequate picture of the geological

structure of the region of surface as well as deep-seated parts. By their scale these maps are the principal type of geological maps that are used for the solution of applied problems.

Detailed geological maps (scale 1 : 10 000, 1 : 5 000, 1 : 2 000 and larger) present a thorough geological characteristics of individual deposits of mineral resources, as well as regions of civil or industrial construction.

According to their scale *geological plans of the horizons* are referred to the geological maps of the detailed type, though they do have specific features of their own. They characterize the attitude conditions of the bodies of mineral resources, their morphology and composition. These plans are compiled not on the basis of mapping, but according to the data of detailed and exploitation prospecting of deposits, exposed by numerous boreholes and underground workings, the special position of which is plotted in compliance with the information furnished by mine surveying.

The Compilation of Geological Maps and Conventional Symbols. There exist standardized rules of making and presenting maps. Any geological map is supplemented with conventional symbols (legend), geological sections, and stratigraphic column, which find their place outside the frame of the map (Fig. 108). On the left-hand side we have the stratigraphic column, the legend is to the right, while at the bottom of the map geological sections are inserted. The inscriptions with which the map is provided are placed either above its northern frame, or below the one situated to the south. Every map is accompanied by numerical and graphic (linear) scales.

The rock characteristics according to age, composition and origin imply the use of various conventional symbols, e. g. colour, striated, alphabetic, and numerical characteristics.

The colour symbols show the age of sedimentary and stratified volcanogenic and metamorphogenic rocks in accordance with international standards (see Table 6). In addition to this the designation of rocks belonging to the lower series of a system presupposes the use of dark shades of colour; lighter shades of the same colour are employed for the rocks of medium and upper series. Bright colours indicate the composition of magmatic rocks (e. g. those pertaining to the acid variety are shown in bright red, the basic rocks have a bright-green colour, the ultrabasic ones are given in bright-violet, and the alkaline rocks are presented as bright-orange varieties).

Striation in the form of dots, dashes, hatches of different degrees of thickness and orientation, triangles, little circles and crosses, etc. is employed to show the composition of rocks of various origin. The main lithological and petrographic types of rocks are represented with the help of simple signs (Fig. 109), while rocks of intermediate composition find their expression in different combinations of these symbols or their more complicated forms. Monochromatic maps can also show the age of rocks. For this purpose striation is employed.

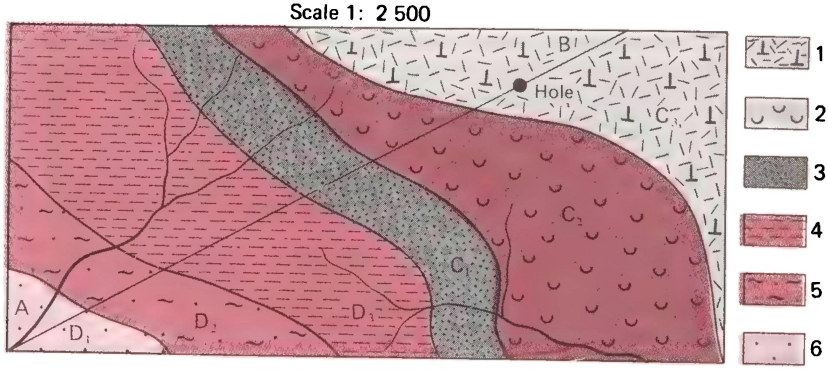
Alphabetic and numerical designations (indexes) serve to represent the age and origin of rocks. The letters of the Greek alphabet are also used to show intrusive and some of the volcanogenic rocks (e. g. γ is employed for acid rocks, δ is the symbol used for intermediate rocks, alkaline rocks are designated by the letter ξ, basic and ultrabasic varieties are shown by υ and σ, respectively).

FIGURE 108. An example illustrating the construction of a geological map, section and column

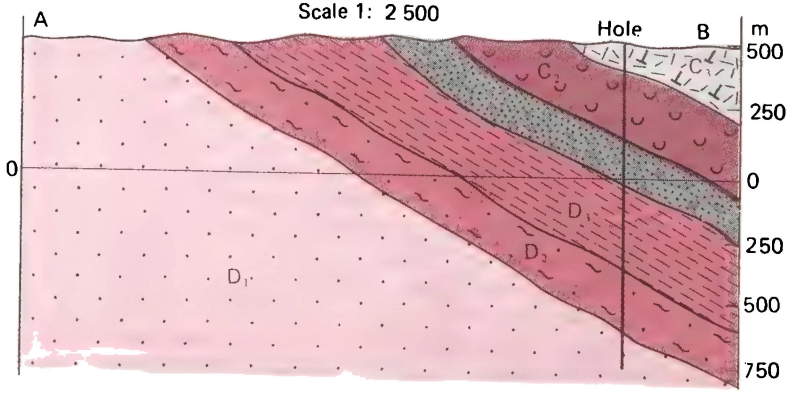
Geological and stratigraphical column

Group	System	Series	Index	Column	Thickness, m	Description of rocks
Paleozoic	Carboniferous	Upper	C_3			Basalt
		Middle	C_2		250	Compacted tuffas
		Lower	C_1		130	Middle sand
	Devonian	Upper	D_3		300	Aleurite
		Middle	D_2		140	Sandy schist
		Lower	D_1			Sandstone

Geological map
Scale 1: 2 500



Geological section along A – B
Scale 1: 2 500



The index for representing sedimentary, volcanogenic and metamorphic rocks is composed of the capitals and small letters of the Latin alphabet and numbers. First comes the capital letter of the Latin alphabet showing the system, at the bottom and on the right-hand side of it an Arabic numeral is placed to show the division, this is followed by the indication of the stage, which is given in Latin small letters, while the numeral that is inserted at the bottom and on the right-hand side shows the substage. For instance, the notation K_1al_3 reads: the upper substage of the Albian stage of the lower division of the Cretaceous system. When necessary, letters are used to designate complexes, series, and suites, as well as for the expression of the origin of some of the sedimentary, volcanogenic and other formations.

The cartographic symbols illustrate key beds (layers and beds), sills, dikes, geological boundaries, dislocations with a break in continuity, the conditions of rock attitude, the orientation of fold bends, the most important paleontological finds and geological prospecting workings.

Conventional symbols are placed in a rectangle and to the right of it the description is given. The distribution of symbols in a legend should be characterized by perfect order. All symbols representing the age of rocks should be given from top to bottom with the age sequence ranging from the young deposits to the old ones. The symbols of magmatic rocks (in the sequence from acid to ultrabasic rocks with intrusive varieties followed by the effusives) are arranged below. Lower still there come symbols of metamorphic rocks (if they are not divided into age groups). The table of conventional symbols ends with tectonic, structural, and other cartographic designations.

The symbolism that is used on the conditional geological maps of the USSR is in compliance with the international system and is regulated by the 1969 'Instruction as to how Sheets of the State Geological Map of the USSR on the Scale of 1 : 200 000' should be compiled and prepared for publication, as well as in accordance with 'The Basic Requirements for the Content and Presentation of the Accepted Geological Maps on the Scale of 1 : 50 000 (1 : 25 000)' issued in 1977.

For the purpose of achieving large-scale geological representations (those of geological plans and sections) at mining enterprises it is recommended to employ the system of conventional symbols, with minor distinctive specifications, that is authorized by the State Standards Committee (GOST 2.857-75) for the presentation of documented graphical materials by mining industry, otherwise known as 'Conventional Symbols to Be Used for Mining Resources, Rocks and Modes of Their Occurrence'. At present, the work on a complete unification of symbols for all types and kind of graphical geological documentation is in progress.

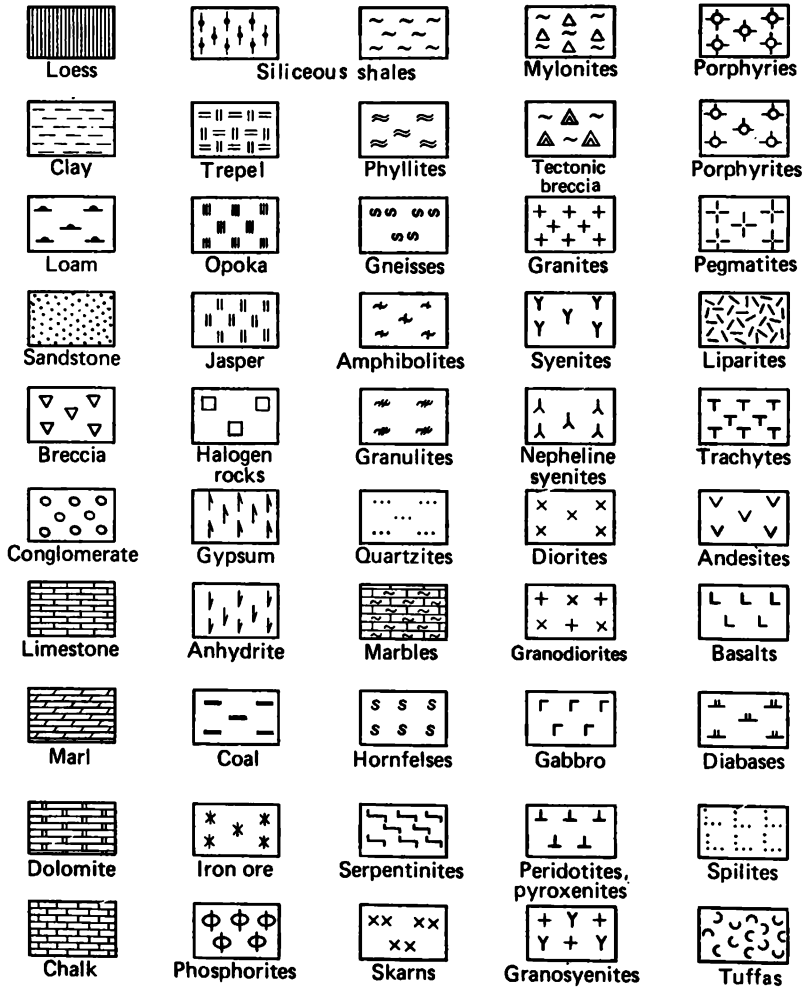
Geological Sections and the Stratigraphic Column. Geological section represents a graphical representation of the geological structure of a part of the territory on a vertical plane. It is compiled in accordance with geological maps or the data furnished by workings of geological prospecting.

The section gives a clear-cut representation of the sequence and thickness of layers, modes of their occurrence, the arangement and forms of attitude on a vertical plane of massifs of igneous rocks and bodies of mineral resources. The

compilation, colouring, and indexation of sections are carried out in compliance with the geological map and conventional symbols.

For the construction of a geological section according to the given direction, the drawing of the topographic profile should first be made on the geological map (see Fig. 108). From the geological map we plot the boundaries of rock masses that are intersected by the direction of the section on the topographic profile. Data concerning the mode of occurrence are used, and the boundaries pertaining to the propagation of masses down into the depth are represented. Above the section we have its name, and vertical and horizontal scales are given

FIGURE 109. Graphical representation of conventional symbols of rocks used in geology



below, while on its sides there are letters showing the beginning and the end of section, and the orientation along compass points.

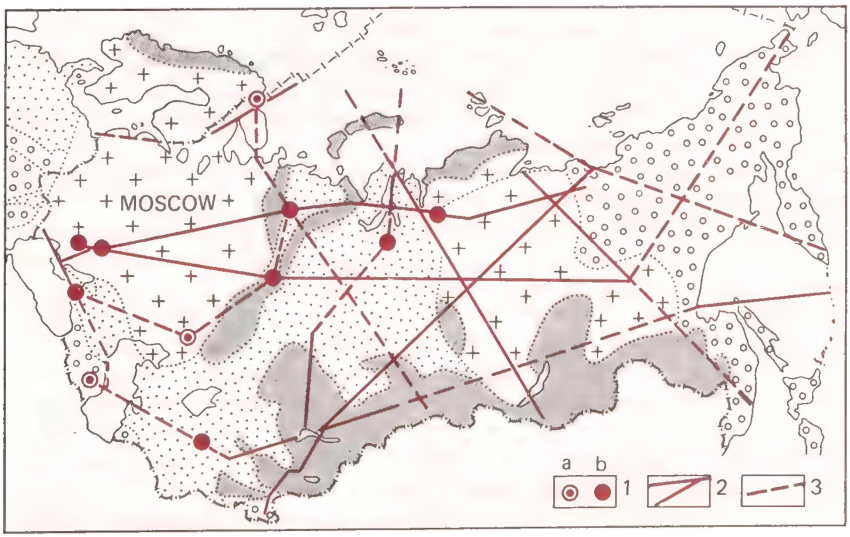
The stratigraphic column constructed on a particular scale represents a sequence in the bedding of rocks, their contacts and material composition (see Fig. 109). The standard form of a column presupposes an image in the centre (with the conventional symbols not coloured), and in columns to the left stratigraphic subdivisions of the generally accepted scale must be arranged. They should range from the systems to the stage, and include their general index. On the right-hand side of the column (in its separate part) the thickness value is given, while the next portion (also isolated from the rest of the material) presents data concerning the characteristic features of rocks.

As a rule, the column is made on a larger scale than the map itself (covering the whole length of the frame). Irrespective of their mode of occurrence the contacts of rocks are shown with a horizontal line (excluding cross-cutting intrusive formations). In conformable bedding the lines should be straight. In the case of unconformity, they remain horizontal, though wave-like.

The other types of graphical materials include drawings of the exposures, geological columns of boreholes and underground workings, as well as special plans and sections with isometric lines pertaining to the values of various geological factors.

FIGURE 110. A diagram, showing the arrangement of deep and superdeep boreholes and deep-seated seismic profiles in the USSR territory:

1 – superdeep (*a*), and deep (*b*) boreholes; *2* – now existing deep-seated seismic profiles; *3* – deep-seated seismic profiles in prospect



Geological Research of the USSR Territory and Its Coverage

Geological mapping is one of the most important methods and the main result of geological investigations. The State Geological Maps present objective data on the extent to which the country has been studied in geological terms.

In 1894 the Sixth Session of the International Geological Congress received the first Geological Map of the European Part of Russia (1 : 2 520 000), which was presented by Geological Committee. Since then geological mapping has held a prominent place in Russian and Soviet geological studies. In 1922 the first Geological Map of the Asian Part of Russia was published, while the Seventeenth Session of the International Geological Congress (Moscow, 1937) saw the first Geological Map of the USSR (1 : 5 000 000), which was edited by D. Nalivkin, who was the chief editor of all geological maps of the USSR for 35 years.

Special mention should be made of those scientists who, within different periods of time, supervised the geological survey in the scope of the whole country and directed the publication of geological maps of various types and scales. They include: V. Obruchev, A. Arkhangelsky, I. Gubkin, A. Borisyak, N. Shatsky, M. Tetyaev, D. Nalivkin, M. Muratov, A. Bogdanov, V. Belousov, A. Peive, Yu. Sheinman, V. Khain, and A. Yanshin.

Over the past ten years the following trends in geological mapping have been developing in the USSR:

the combination of general and detailed geological and cartographic works, which finds its expression in the compilation of state geological maps on the scale of 1 : 1 000 000 (new series) and 1 : 50 000;

the compilation of various nontraditional maps of geological content, reflecting the structure of given horizons of the earth's crust, as well as an all-round characteristics of its structures and material composition;

the publication of sets of maps covering exactly the same areas that supplement each other with respect to their content;

a wide-range complex use of remote sensing and geophysical methods in the compilation of maps of the earth's surface and deep-seated structures;

the elaboration of methods pertaining to the geological mapping of shelf and more abyssal zones of seas and oceans.

By 1983 the territory of the USSR had practically been fully covered with the medium-scale geological survey, with 30% of its territory surveyed on a large scale. The results of geological survey and other special scientific research works were given a synthesized form by the Soviet geologists in a number of large cartographic generalization that were submitted to the 27th International Geological Congress (Moscow, 1984). This included series of maps on the scale of 1 : 2 500 000, 1 : 5 000 000, and 1 : 10 000 000, sheets of State Geological Map of the USSR (scale 1 : 1 000 000). Besides, publications comprised maps of faults, sedimentary and volcanogenic formations, magnetized formations of the earth's crust, the space and geological map, atlases of geophysical, hydrogeological, geological engineering maps of the USSR, as well as sets of maps of geological content related to individual regions of the country.

The further development of the research concerned with the geological study

of the USSR territory presupposes the implementation of a comprehensive programme, which includes the investigations of the deeper structure of the earth's crust and its upper mantle. What lies at the bottom of the programme is the creation of a network of intercorelated deep-seated geophysical profiles, corresponding to the drilling of deep- and superdeep boreholes and remote sensing applications (Fig. 110).

This enormous programme is successfully being carried out at present.

VI Technogenic Changes of the Geological Medium

Let us not, however, flatter ourselves overmuch on account of our human victories over nature. For each such victory nature takes its revenge on us. Each victory, it is true, in the first place brings about the results we expected but in the second and third places it has quite different unforeseen effects which only do often cancel the first.

F. ENGELS. *DIALECTICS OF NATURE*

Chapter 22 Technogenic Changes of Geological Objects

The Concept of Technogenesis

The field of geological activity of man is the geological environment which covers the actual physical space that includes the upper part of the earth's crust and partially the outer layers of the Earth interacting with it.

The geological environment is formed as a result of the complex activity of the earth's outer layers and the influence of endogenic and exogenic agents on the geological processes. For millions of years the nature's equilibrium was only determined by natural factors. However, with the development of society and particularly under contemporary conditions, the influence of man upon nature has become much greater. In conditions of modern scientific and technical revolution this kind of artificial intrusion of man into environment results in marked disturbances of nature's equilibrium, while in a number of cases this becomes responsible for the consequences which can have a global character.

According to its scope and intensity the influence of man upon the environment can already be compared with the main nature formation processes. Ten per cent of the fluvial runoff (about 3.5 thousand km^3 of water) are annually employed for domestic purposes and 3 000 km^3 of soil are displaced in the process of ploughing. 120 bln tons of ores, combustible fossils and building materials (by the year 2 000 the figure will reach 600 bln tons) are extracted from the earth's crust; hundreds of billions of tons of ground are dislocated in the operations connected with construction and removal; 500 mln tons of mineral fertilizers and more than 4 mln tons of various toxic chemicals are spread over the fields. About 600 km^3 of industrial and domestic sewages are discharged into the water basins, which, when cleaned, still require to be diluted with pure waters 8-12 times. A large number of chemical substances enter the medium in such quantities which are 10-100 times greater than their natural replenishment as a result of natural processes. Every year people burn up to 9 bln tons of conventional fuel (1 kg = 18.7 thousand kJ of heat), and in addition to this over 20 bln tons of carbon dioxide and more than 700 mln tons of other gaseous compounds, as well as carcinogenic hydrocarbons are discharged into the

atmosphere. The mass of substance that is annually displaced in the course of industrial activity comprises not less than $2 \cdot 10^{13}$ tonnes.

The sum-total of all forms of impact exerted by man on the geological environment is called *technogenesis*. These influences are conditioned by construction engineering, agricultural, hydrotechnical, mine engineering and other types of human activity. Of all the types of technogenesis *mine engineering works* are the ones that are of greatest significance, since these are connected not only with the surface, but also with the interior parts of the earth's crust.

The whole range of technogenic influence of man upon the geological environment is called *technosphere*, or *noosphere*, i.e. the region wherein the rational influence of man and his technology on the geological environment find their expression. The technogenic influence is always directed at a given part of the earth's crust and brings about consequences that are interrelated by the properties and processes of the given part of the geological environment on the one hand, as well as by the character and intensity of the impacts, on the other. The most substantial geological factors are the following: *the tectonic and geological structure of the region, the geomorphological and physical and geographic characteristics, hydrogeological*, and *geological and engineering conditions.*

The consequences of technogenic influence are primarily determined by the correspondence of the territories to the structural elements of the earth's crust – the platform and geosynclinal regions. The differences are conditioned by the dissimilar structure and composition of the upper part of the lithosphere; the development of folded and rupture dislocations, which influence the stability of rock massifs, their permeability for waters and gases; and the tectonic activity. The degree to which the relief is dissected, the steepness of slopes, and the physical and geographical zonality determine the direction and intensity of development of some processes of technogenesis, and the extent of geological environment change. The properties of rocks entering into the composition of the geological section, the characteristic features of water-bearing horizons and complexes, the relationship of water-bearing and impermeable rocks in the section, the composition and regime of the movement of underground waters are the factors the function of which can hardly be overrated in the development of technogenesis.

The consequences of the technogenic influence on the geological environment are divided into *mineragenic, geochemical, geophysical, geodynamic, geomorphological, hydrogeological* and *geological and engineering types.*

The mineragenic and *geochemical* consequences are conditioned by the redistribution increase of the substance of the earth's crust in mining, construction, and hydrotechnical operations. Mineragenic consequences are manifested in the depletion of mineral resources and cause changes in the technological conditions pertaining to the development of deposits. Geochemical consequences of technogenesis consist in the disturbance and transformation of the chemical balance of substances in the geological environment, the changes of the natural ecologic equilibrium in the lithosphere-atmosphere-hydrosphere boundary layer.

Geophysical consequences find their expression in the manifestation of artificial

physical fields (stray currents, seismic, and acoustic waves, etc.) in the upper part of the earth's crust. These fields exert their influence on the substance of the lithosphere, enhance the corrosion of metals, increase the forcefulness of water, and so on. *The geothermal consequences* of technogenesis are expressed in the conditions of heat alteration of lithosphere surface, the water and heat regime of channels and basins. These consequences are particularly tangible in permafrost regions.

The geodynamic consequences of technogenesis consist in the disruption of the geostatic field in connection with the drifting of mine workings, the redistribution of great masses of water on the surface, the extraction from the depths of considerable amount of rocks and mineral resources, including oil, gas, and underground waters. *The geomorphological consequences* find their expression in the creation of a technogenic relief and the change of the primary relief of the territories as a result of the disturbance of equilibrium between accumulation and denudation processes.

The hydrogeological consequences of technogenesis emerge when the impact upon the water-bearing horizons is either direct or indirect. They are manifested in the change of the resources, levels, regime and the quality of underground waters. *The geological and engineering consequences* are expressed in the activization of slide, talus and suffosion processes, as well as in the manifestation of other exogenic processes, which may not be typical of the given physiogeographical or geological situation.

Technogenesis does not only change the properties and structure of geological objects, but also creates new technogenic ones. The exogenic technogenesis actively influences the processes and results of external geodynamics, especially in weathering, denudation and accumulative work of surface and underground flowing waters, the activity of sea, lakes, swamps and wind, and is substantially reflected in the processes of diagenesis. At the same time technogenesis gives rise to processes, which resemble some of the natural phenomena of internal geodynamics (oscillatory and dislocation movements, earthquakes, magmatism, metamorphism, and changes of physical fields).

Technogenic Changes of External Geospheres

The Changes of the Atmosphere. The Earth's original atmosphere was of the reducing type and consisted mainly of methane, ammonia, and water vapours. When vegetation emerged, the reactions of photosynthesis changed the composition of free air into that of the nitrogen and oxygen variety, and the atmosphere became oxidative. Under the impact of engineering and economic activity of people the gaseous equilibrium began to be disturbed. Approximately over the past one hundred years the concentration of carbon dioxide rose from 0.027 to 0.0325%, and in the coming century it can go up to 0.038%, if its release into the atmosphere remains on the same level. The compounds of sulphur also enter the atmosphere in great quantities. Their main sources are energetics, nonferrous and ferrous metallurgy.

The change of the gaseous composition of the atmosphere, especially its enrichment with carbon dioxide can, in the opinion of many scientists, cause

global changes of the climate. By the year 2000 the temperature rise can comprise 0.5 °C, while the further temperature rise will have disastrous consequences.

The excessive amount of dust serves as the prerequisite for the enhanced capability to reflect the Sun's rays, gives rise to the development of cloud canopy, accelerates the rate of thawing of mountain glaciers and snow in connection with their pollution by settling down dust. Besides, the accumulation of dust hampers the counter thermal flow of the Earth, and the thus conditioned greenhouse effect increases the temperature of the air on the planet.

It would hardly be possible not to mention the thermal pollution of the atmosphere either. A major part of the produced energy is discharged into the atmosphere in the form of heat. As a result of the consumed energy enhancement in comparison with solar radiation the temperature difference in cities and neighbourhood can be higher than 1-2 °C, while in some cases it can reach even 10 °C. There is some reason to believe that in one hundred years' time the amount of technogenic heat emitted into the atmosphere will be equal to that received from the Sun.

The Changes of the Hydrosphere. Direct and indirect impacts of man upon the water layer, which introduce quantitative and qualitative changes, alter the water regime of the planet and the geological role of the hydrosphere in a substantial way.

Several types of water pollution are distinguished: *domestic, agrochemical,* and *industrial.* It is usually difficult to draw a clear border line between the said types.

The domestic pollution is conditioned by the detergents which are characterized by chemical activity and stability. The pollution of waters by organic decomposed substances leads to the depletion of reserves of the oxygen dissolved in water.

The agrochemical pollution of waters is conditioned by constantly increasing use of fertilizers and toxic chemicals in agriculture. The atmospheric precipitations wash out the fertilizers and toxic chemicals when percolating through the soil and plant layer and introduce them into the surface and underground waters. This leads to a marked increase in the concentration of a number of substances, particularly nitrates, in water, and sometimes makes the underground waters unsuitable for drinking.

The washdown of agrochemical products into closed basins results in their eutrophication, i.e. to the increase in the concentration of nutritious salts (predominantly phosphates) in water, and the profuse growth of algae, plankton and others. Eutrophication has a deteriorating effect on the quality of water, the degradation and extinction of flora and fauna, while the lakes themselves gradually 'die out' (e.g. Lake of Geneva, Erie Lake and others).

Industrial pollution is conditioned by the discharges of industrial wastes and has a global character at present. The industrial wastes removed into channels and basins contain a large amount of harmful and toxic elements, which, as a rule, do not easily lend themselves to either dissolution or decomposition.

A particular place among these pollution agents is attributed to petroleum products and radioactive wastes. A single drop of oil on the surface of water forms a spot with the diameter of 0.3 m. The thinnest possible film of oil isolates

water from the atmospheric air, alters the regimes of carbon and oxygen exchange, lowers the evaporation, and disrupts the ecological balance. Every year the ocean receives more than 6 mln tons of petroleum products. What causes concern is the growing concentration of radioactive particles in certain regions, conditioned by the fact that radioactive wastes are buried in the ocean.

The pollution of the World Ocean is becoming a global phenomenon. It has been estimated that not less than 25 mln t of iron, nearly 400 000 t of zinc, copper and manganese, over 180 000 t of lead and phosphorus, and up to 3 000 t of mercury enter the water of the oceans every year. The mass of oceanic waters serves as a gigantic filter, since organic and mineral substances brought from the continents are decomposed, dissolved, and deposited on their floor. However, recently, in connection with a marked increase in the scope of technogenic pollution the ecological balance between the processes of pollution and filtration of waters is becoming destabilized. When the absence of effective measures on the prevention of excessive pollution takes place the disturbance of equilibrium can become irreversible.

The underground hydrosphere provides approximately 25% of the general consumption of drinking, technical, domestic and other kinds of water. That is why any change in the composition of waters as a result of technogenesis has an immediate effect on the conditions of water supply. The chemical composition of underground waters changes under the influence of the pollution of atmosphere, the surface basins, snow cover, the earth's surface (in cases of the accumulation of wastes, fertilization and chemical toxication), incorrect regime of irrigation, the disposal of industrial and domestic wastes, the underground burial of industrial wastes (including the radioactive ones), the escape of sewerage, oil pipes, etc.

Changes resulting from technogenesis are most typical of near the surface water-bearing horizons on the territory of industrial towns, commercial enterprises (including those of the ore mining type), and agrocomplexes. The pollution of underground waters reduces the water resources that are necessary for human consumption. The change in the chemical composition of underground hydrosphere is connected with the development of such geological processes as salinization and cementation of grounds, chemical suffosion, the formation of karst, deconsolidation of clay rocks, etc.

In addition to chemical and biological types of pollution a highly significant consequence of technogenic impact on the hydrosphere is the heating of surface and underground waters, which is conditioned by the constantly high temperature of drainages. The principal sources of thermal drainages are metallurgy and energetics, particularly that of atomic variety. The temperature of waters (mainly the underground ones) also enhances the activity of urban centres. The heating of surface and underground waters under the activity of various factors can finally reach 10-15 °C and more. It is assumed that in the nearest future the heating will be spread to the coastal-marine waters of the oceans.

An important consequence of the impact of technogenesis upon the hydrosphere are the changes of the levels of surface and underground waters. Over the past decades there has been a marked alteration in the regime of rivers, the water reservoirs smooth out the seasonal changes of the levels and the consumption of water and reduce the flow rates. Under the activity of enterprises

and populated areas in connection with powerful intake and pollution of water, thousands of small rivers are growing shallow, dry up, and often disappear.

The changes in the underground hydrosphere are usually manifested down to the depth of 100 m, but often penetrate to deeper horizons as well. The lowering of the level of underground waters is mainly conditioned by the extraction of water from the depths or by the decrease of its supply from the surface for the alimentation of water-bearing horizons. This takes place in the course of an intensive pumping of water for supply purposes, and in connection with mining and building operations, drying up the locality, a decrease in the infiltration of atmospheric water and the liquidation of surface water basins. Besides, decrease can be local and regional, temporary and age-long one.

The lowerings of ground water levels (the so-called depression cones) emerge in connection with the continuous exploitation of underground waters in cities and industrial centres. Their diameter can reach scores and hundreds of kilometres, while their depth comprises scores and hundreds of metres. Depression cones of still greater dimensions appear in the regions characterized by the recovery of mineral resources in connection with the pumping of water during surface and underground mining processes.

The reverse phenomenon, i. e. the rise in the level of underground waters, is conditioned by the creation of reservoirs, canals, ponds, the stoping of underground waters, the flooding of oil deposits, the leakage of water from basins, water-supply and sewerage systems, snow retention, irrigation of fields, etc. Usually the increase value ranges from 0.5 to 100 m, though in some rare cases it exceeds 10-15 m. The maximum increases of level (60-100 m) are connected with mountain reservoirs.

Technogenic Changes of the Earth's Crust

Changes in the Composition and Structure of the Earth's Crust. The composition of the earth's crust undergoes most prominent changes in near-surface part – fact that can be accounted for by constantly increasing level of recovery and use of mineral raw materials. Under the existing technology of recovery practically half of the metals and one-third of chemical raw materials are lost.

As a result of mining operations the number of chemical elements in the earth's crust is greatly reduced. Thus, up to the present moment more than 100 mln t of copper, lead, zinc, tin, and aluminium have been extracted and carried out on to the surface.

Out of the whole mass of recovered mineral resources, the preponderant part has been extracted within the past 20 years. This includes 75% of oil, 40% of coal, 50% of iron, and 90% of combustible gases. The recovered chemical elements (e. g. metals) are dispersed on the Earth's surface, undergo oxidation, migrate, and are accumulated in favourable conditions. There takes place a continuous 'ferruginization' of soil. In the most inhabited part of the planet every square kilometre of the surface had received approximately 270 t of iron by 1980. Besides, in the twentieth century the content of iron per 1 km^2 of the surface has been growing by 6 t every year. The technogenic migration of lead and copper

considerably exceed its natural migration, while that of zinc and manganese approaches the values of their natural migration. As a result of the burning of coal the environment receives 700 times more mercury, 125 times more arsenic, 60 times more uranium, and 40 times more potassium than their content in natural biological circulations. The recovery and evacuation of chemical elements on the surface will continue to be on the increase. It is assumed that in ten years' time in the surface part of the earth's crust the content of iron oxide will be twice greater than it is now, that of lead will grow by 10 times, while the content of mercury and arsenic will be 100 and 150 times more, respectively.

The economic activity of man is often contrary in its orientation to that of natural processes. When mineral fuel is used man disperses carbon dioxide in the earth's crust. Fertilizers are purposefully spread over vast areas. Dispersion, however, does not exclude the fact that a large number of metals are still preserved in the earth's crust.

Thus, the predominant trend in the geochemistry of technogenesis is the dispersion of valuable chemical elements.

The redistribution of substances in the earth's crust does not only change its composition, but also disrupts the natural processes relevant to the migration of chemical elements in nature, the consequences of which cannot yet be estimated.

The civil engineering activity creates an additional load on the masses of rocks and usually causes restricted dislocations. The main results of the construction works should be considered to be the compression and consolidation of rocks under individual buildings and populated regions on the whole. At present after every 15 years the earth's area planned for construction purposes is becoming twice greater. By 1980 the territory occupied by all engineering structures comprised about 5%, while according to the prognosis made for the year of 2 000 it will reach 15% of land.

The most prominent dislocations in the structure of the earth's masses emerge in the course of the hydrotechnical construction, where the natural equilibrium can sharply change in connection with the excess of critical point of the stressed state of rocks. Tectonic dislocations can also be the results of a marked change in the properties of rocks, conditioned, for instance, by their saturation, when the conditions of natural filtration change. There are widely known cases of enormous disasters of such hydrotechnical structures as the Buzay dam in France (1895), Austin (1890) and St. Francis (1938) dams in the USA and others.

The mining engineering activity is immediately connected with the depths of the Earth, and hence its consequences are usually more substantial. Mining construction and recovery works disrupt the composition and structure of rock massifs; they create considerable cavities and voids, the scale of which exceeds the natural formations, such as underground karst caves. In the process of mineral resources recovery man penetrates into the great depths of the earth's crust. For instance, the underground workings of 'Kolar' mine in India reached the depth of 3 800 m; the mining of gold and uranium ores in South African Republic is carried out at the depth of approximately 4 km. The oil boreholes have reached still greater depths.

As has been pointed out earlier, the drifting of mine workings, the extraction of

hard mineral resources and concomitant rock mass, oil, gas, and underground waters causes disturbances of the geostatic field and conditions the manifestation of geodynamic consequences of technogenesis, as well as the disruptions in the structure of the upper part of the lithosphere. When the surface above the underground workings collapses, pits and sinks are formed. They can reach the depth of several scores of metres. Local pits of the surface are found in many regions where ores and coals are recovered by means of underground mining. There is some reason to believe that phenomena of this kind will gain more ground in their development in connection with the use of highly productive systems in the course of underground mining with the collapse of ore and enclosing rocks (without any support of the worked out space).

Vast regional subsidences of the territory (up to 5-10 m) emerge as a result of the lowering of rock pressures in connection with the pumping of fluids and gases from the depths. In some cases similar type of subsidences can have disastrous consequences.

In special publications we can read of numerous instances concerning the changes in the lithosphere, which emerge as a result of the subsidence of the surface when rock pressure is lowered. Great subsidences (measuring several scores of square kilometres) with the amplitude of about one metre have been recorded, for instance, on the oil production territory of Texas (USA). The warping of the surface in the oil structure region of Wilmington (California, USA) reached 8 m and brought about the catastrophic destruction of buildings, bridges, roads, and industrial enterprises (1957). The pumping of underground waters in Mexico City resulted in the subsidence of the city's surface to almost 9 m. For the same reason the territory of Tokyo has subsided by 3.5 m within the period of half a century.

Changes of the Relief. The relief of the Earth's surface changes when the construction of cities, roads, hydrotechnical, energetic and other structures is in progress. However, what chiefly accounts for the increase in the contrastivity of surface marks is mining industry, since in this case positive, as well as negative, forms of the relief are created.

More considerable in depth and area depressions are those that are formed in the open-cast (quarry) recovery of mineral resources. The depth of quarries now reaches 300-800 m; the quarries that are being planned presuppose the depth of up to 1 000 m, with the length of their fields measuring 2-5 km.

The regions of mining industry are characterized by a technogenic relief of ridges and hills, which was formed during the storage of barren rocks and wastes of the reworking of mineral raw materials. The tendency along which the transformation of the lithosphere's relief is constantly accelerated is found to be prevalent.

As in the case of sedimentogenesis, exactly the same stages of denudation and accumulation of substances are distinguished in technogenesis. The negative forms of the relief are conditioned by technogenic denudation, i.e. the displacement and removal of rock mass. The positive forms are created owing to technogenic accumulation (rock piles, spoil heaps, barrages, tailings dumps, slime accumulators, etc.).

Civil engineering aims at levelling out the Earth's surface. For this purpose the lowered parts are filled, while the elevated ones are truncated. At present the regulated areal raising of marks has been widely used in building and improvement of any territory. The height of artificial terraces varies from 1 to 15 m, while that of alluvial sandy massifs comprises 2-8 m.

At the same time, and in a large number of cases, the relief marks are lowered for construction purposes, viz. mountains, hills, benches, dunes, barkhans, hummocks, and other positive forms of the relief are sheared. The value of truncation can reach 50 m and more, while the scales of these operations, particularly in the regions characterized by mountainous or piedmont relief are markedly considerable.

Thus, the general regularities of the technogenic transformation of the relief are: the tendency toward levelling out of the relief; the gradual disappearance of natural microrelief; the development of positive and negative forms of the microrelief with the predominant tendency to elevation of marks above the depression at the expense of the extraction of the rock mass from the depths and the storage of industrial wastes on the surface.

Chapter 23 Technogenic Changes of Geological Processes

Under the influence of human activity natural geological processes undergo quantitative and qualitative changes. They are enhanced, slackened, and sometimes cease to function altogether, stop being wholly natural, and acquire the features and orientation of technogenic manifestations. To a greater extent technogenesis brings about changes in the geological processes connected with the activity of atmosphere, as well as surface and underground waters. Technogenesis influences the processes of internal geodynamics to a much lesser degree.

Technogenic Changes of Exogenic Geological Processes

The processes of weathering experience either direct or indirect influence of technogenesis. The latter plays the part of either an active agent of weathering, or exerts its influence on the natural agents of this phenomenon (temperature, humidity, composition of air, water, and organisms), as well as on the medium (geological and hydrogeological conditions, relief and others).

The result of direct impact is the formation of *technogenic* (anthropogenic) *weathering crust*, which is formed owing to the destabilization, disintegration, and change of the composition of rocks that are displaced in mass quantities in the course of open-cast and underground mining operations. Weathering is most intense in the edges of quarries, heaps of rocks, scarps of channels, road pits, as well as in adits, tunnels, and other underground workings.

Direct impact can also be accounted for by agricultural activities. Ploughed

soil is, to a great extent, subjected to temperature, oxygen, atmospheric moisture, microorganisms, etc.

The indirect impact of technogenesis upon the agents and medium of weathering can either enhance or slacken the progress and results of natural processes. For instance, the activity of water, carbon dioxide, and temperature is found to be on the increase in conditions of technogenesis, while that of oxygen and solar radiation diminishes in its value. At present, more than half of the area of land is covered by weathering of technogenic character. The maximum depths of its development is determined by the depth into which mining operations are penetrated.

Water erosion is a geological process which has recently acquired a highly intense development. The activity of man – the change of relief, vegetation, water regime, microclimate, etc. – promotes the intensification of erosion by means of activizing the now functioning factors and conditions of different types of erosion and creating new ones, among which surface and linear varieties share the leading role.

The development of surface erosion is predominantly connected with agriculture. Linear erosion, e. g. the formation of ravines, road, irrigational and fluvial kinds of erosion, is conditioned by both the agricultural works and the development of cities, enterprises of mining industry, and others. Ravines of the greatest extension are confined to the elevated plains, and those regions that are characterized by a greater degree of ploughing and the development of cities. The rate at which the ravines grow comprises several metres per year, and in some cases the figure can be as high as 100 m.

The development of specific types of linear erosion is also encouraged by the construction of roads and irrigation. The area of irrigated agriculture is constantly becoming larger in all the countries of the world. Irrational consumption of water, its excessive supply, and the considerable gradients of irrigational structures result in the downwash, washout, and aggradation of soils. In addition to this, irrigational erosion can account for more than 100 t per acre loss of soil every year.

Technogenesis also serves to give impetus to the development of *wind erosion*, in which deflation has the leading role. The wind activity is, to a great extent, confined to the medium inhabited by man, since technogenesis, viz. the destruction of vegetation, ploughing, and desiccation of soils, the arrangement of terraces, embankments, etc. activizes the work of wind. There are enormous territories that are most favourable for the development of eolian processes. Drifting sands and dust storms have recently acquired an elemental character and cause great damage to national economy.

Marine abrasion, which has become more active due to the interference of man in natural processes is now widely spread. Abrasion is also made more prominent by such phenomena as a marked reduction of the hard run-off in the sea, the depletion of the sources of natural alimentation of beaches, the use of sandy and pebbled material for economic purposes, etc. The washout of shores is becoming more prominent, and the areas of beaches are on the decrease. At present the rate at which shores are destroyed has reached the figure of 4-6 m a year. The scales of marine abrasion have become considerably greater, and

approximately 40-60% of sea shore length have become subjected to it. The results of abrasion, brought about by the increasing interference of man, are particularly apparent in places of resort, where under its impact there is a marked decrease of the size of beaches, the destruction of roads and other structures. The implementation of measures directed at the stabilization of shores call for considerable monetary funds and do not always bring the desired effect.

Technogenic activities (the recovery of mineral resources by means of underground leaching, subsurface construction, intensive use of underground waters, the destruction of vegetative cover, the disposal of waste waters, etc.) cause and promote the development of processes known as *the formation of karst*. The enhanced technogenic karst differs from natural variety by a greater rate of its growth and intensity of manifestation, smaller area, as well as the depth of its propagation. Technogenic karst is widely developed in carbonaceous, gypsum and anhydrite, and saline rocks.

Technogenic kinds of impact on natural geological processes are closely related to such geodynamic phenomena as *taluses, collapses,* and *landslides.* Taluses are actively developed in the artificial exposures of quarries, excavations made during construction works, road pits and embankments. The movement of taluses along the slopes and scarps is caused in this case by the disposal of waste waters, snow, vibrations, explosions, etc. The emergence of taluses acts favourably on the truncation of slopes, the utilization of forest, blastings, the impact of artificial water basins, and when the irregular mining and civil engineering works take place.

Man's activity proves to be an active factor conditioning the formation of landslides. It is assumed that 80% of all contemporary landslides are of technogenic nature. Landslides can be the immediate result of the truncation of slopes and scarps, their excessive loading due to construction works, flooding, humidification, blastings, etc. The intensification of landslide phenomena calls for the undertaking of concrete measures on their prevention and the restriction of hazardous consequences.

Processes Similar to Those of Endogenic Geological Nature

The processes discussed below can only tentatively be called endogenic. The fact is that they are brought about by technogenic, i. e. external impacts of man on the earth's crust, though by a large number of features they do remind us of some of the processes of internal geodynamics.

The local warpings of the earth's crust with the amplitude of up to several metres, that have much in common with natural oscillatory movements, are conditioned by the production of oil and the mining of underground waters, the static load of structures built on land, and the intensity of the movement of land transport facilities.

When the pumping of oil, gas and water is intensive, there takes place a warping of the surface of the earth's crust, which is of maximum amplitude (from 0.5 to 9.5 m). The rate of subsidence can reach 3-8 and even 20 cm per year, which is much more prominent than under natural tectonic oscillations of the

earth's crust. Special mention should be made of the fact that when the pumping out ceases and when the water is delivered into the depths the subsidences of the surface are retarded and even stopped altogether.

In some cases the subsidence of the surface is accompanied by a break in the continuity of rocks with the emergence of gaping faults and fissures. Thus, during the warping of the earth's surface, in the State of Arizona (USA) there appeared gaping fissures that were several centimetres wide and some kilometres in length. A large 700 m long and 5 cm wide fault was formed in the rock wall on North Island in New Zealand during the laying out of a submarine tunnel for a hydropower station. At the Ingwood (USA) deposit in connection with the production of oil and the pumping of water into deeper regions the existing ruptures were activized and new fissures appeared. They measured from 130 to 830 m in length and up to 15 cm in width.

Tectonic displacements of various range and extension also emerge when nuclear explosions take place. Thus, during the underground nuclear explosion of about 5 Mtn on Amchitka Island (USA) there appeared a system of fissures and ruptures with the displacement along them, while the marine terrace at a distance of 1.5 km from the epicentre of the explosion was found to be elevated by 0.6-1.1 m over 2 km. The appearance of large faults with vertical displacements were at nuclear explosion in Nevada at a considerable distance from epicentre.

Nuclear explosions are also accompanied by such particular tectonic phenomena as *earthquakes*. According to the value of seismic effect, some explosions (nuclear and non-nuclear ones) are no less prominent than natural dynamic agents. Thus, for instance, numerous powerful shocks were recorded after the nuclear explosions described above. In the State of Colorado during a nuclear explosion a 5.5 point earthquake was registered at a distance of 80 km from the epicentre.

Technogenic earthquakes are caused by the influence of large water reservoirs, the exploitation of oil deposits, the pumping in of fluids in the depths, mine shocks in underground workings, etc. At present, seismic phenomena are registered at 40 large water reservoirs. Powerful shocks were registered at the water reservoirs of Mead (USA), Kariba (Africa), Montaqnar (France), Kremasta (Greece), Kurobe (Japan). In some cases (Kurobe and Kremasta) the technogenic earthquakes had disastrous consequences.

Seismic effects have also been recorded during the production of fluids. In the USA, near Denver City, underground shocks were registered when industrial discharges were pumped in to the depth of more than 3 600 m.

All the instances illustrating the manifestation of technogenic earthquakes discussed above are connected with the filling of water reservoirs, the extraction or pumping in of fluids into the depths, conditioned by the redistribution of stresses in the earth's crust. In cases like these technogenic agents become responsible for the seismic prospecting of the accumulated elastic energy.

Powerful nuclear explosions are accompanied by the phenomena that are similar to the natural processes of *magmatism* and *metamorphism*. In the moment of explosion the temperature reaches millions of degrees, while pressure measures tens of thousands of MPa. In the centre of explosion the rock becomes

transferred into vapour; at a certain distance it is melted, and, still further, gets markedly heated. Thus, depending on the power of explosion zones of different degree of heating of rocks are formed. In the proximity of the centre the type of melt is formed, which is very much the same as magma, while at some distance, where the rock is considerably heated, conditions pertinent to metamorphism are created. These regularities are substantiated by drilling carried out within the zone of explosion.

Technogenic factors also give rise to conditions that are relevant to *the changes of the Earth's physical fields.* Nowadays this question has not yet been sufficiently studied, and it is possible to adduce only some examples illustrating this phenomenon. Thus, for instance, the anomalies of the natural electrical field are, to a great extent, conditioned by the development of electrification. The level of radiation, enhanced as compared with the natural background, was conditioned in its time by numerous tests of nuclear arms. This level was reduced only after the tests in the atmosphere, hydrosphere, and on the surface of the Earth were prohibited. In their turn, the underground nuclear explosions had only a local impact on the magnetic field of the planet, which was determined by a large number of measurements.

The Protection and Rational Use of Geological Environment

Some of the examples and general regularities that have previously been discussed in connection with the influence of man on the components of natural environment and geological processes make it possible to regard technogenesis as an important and global factor of geological development of the planet. The results of technogenic influence on the atmosphere, hydrosphere and biosphere, the composition and structure of the earth's crust, and forms of its relief can hardly be overestimated. The changes of natural objects and processes are sometimes so great that the disturbances of individual elements of natural equilibrium can become irreversible. It is difficult to say anything about the consequences of such disruptions in advance, though the deterioration of the quality of environment is already now becoming a serious obstacle in the development of the productive forces of society.

Within the past few decades the problem of environment protection has become one of the main problems with which people are concerned. The scientific and technical progress and the accelerated economic development of the world's national economy, the rapid growth of population on the planet and many other processes are accompanied by a marked worsening of the quality of environment, the depletion of the reserves of natural resources, the pollution of air, fresh waters, the destruction of lands and soil cover. These processes are practically manifested everywhere and cause a disturbance in the circulations of substance and energy, in global and regional geochemical cycles, and disintegrate the structure of natural landscapes.

The study and investigation of processes that emerge and occur in the complex system of 'man-geological environment', the analysis of the impact of scientific and technical progress on nature render it possible to substantiate the optimal

conditions pertinent to the interaction of the society with the environment. Hence, the environment protection and its optimization may well be regarded as a global problem. There are numerous examples when the discharge of noxious substances into the environment cover enormous territories, disregarding any national borders. The poisonous gases which are ejected into the atmosphere by the plants and factories in Great Britain, Belgium, and FRG move eastwards and to the northeast, thus polluting the territories of Scandinavian countries and Eastern Europe. Five states account for the pollution of Rhein River and eight countries contaminate the waters of Danube River. Examples of this kind could easily be multiplied. This situation makes international cooperation in protecting the environment absolutely essential.

The scales and types of impact on natural resources are studied within the framework of national and international programmes on monitoring the environment, i. e. in the system of observations and control over the state of territories or aquatoria with the aim of rational use and environment protection. They include: the Interstate Programme 'Man and Biosphere'; International Biological Programme 'Universal Strategy of Environment Protection', elaborated by the International Union for the Protection of Nature and Natural Resources; investigations of the International Committee for the Protection of Mountain Regions; the Environmental Programme referring to the categories of UNO central bodies.

By 1984 226 protected natural territories (standards of environment) had been organized in 62 countries. New aspects of the problems pertaining to environment protection are discussed in the International Programme 'The Protection of Lithosphere as Part of the Environment'. One of these aspects is the protection of lithosphere from the penetration of technogenic pollutions in the form of highly concentrated discharges of industrial waters.

The conference on security and cooperation in Europe and the signing of the First Treaty in Helsinki in 1975 was of enormous significance for strengthening international cooperation on the environment protection. According to this document the policy of the states that participated in the conference should be based on the following principles: the protection and improvement of environment, the protection of nature, and the rational use of its resources.

The most important feature of the cooperation of Socialist countries in the field of environment protection is their orientation towards rendering mutual assistance in the solution of the urgent tasks of nature management. A joint research connected with this problem was initiated in 1964. In 1971 an agreement was signed on the scientific and technical cooperation on the complex programme 'The Elaboration of Measures on the Environment Protection'. This programme comprised six problems: (1) the hygienic aspects of environment protection; (2) the protection of ecosystems and landscapes; (3) the protection of atmosphere from noxious substances; (4) the protection of water resource; (5) the liquidation and utilization of domestic and industrial wastes; (6) social and economic, legislative and pedagogical aspects of the protection of nature. For the carrying out of joint scientific investigations a special administrative body dealing with the problems of the protection and improvement of environment was organized at the Council for Mutual Economic Aid. Under the guidance of

this council 'The General Detailed Programme of the Cooperation of CMEA Member Countries in the Field of Protection and Improvement of Environment and the Correlated Use of Natural Resources' is nowadays being implemented.

What serves as the legislative basis for the protection of nature in the Soviet Union is the Constitution of the USSR adopted by the Supreme Soviet of the USSR in 1977. The Constitution generalizes the experience in the development of nature protection legislation and also sets out aims, tasks and the main problems in the state and public activity in the field of environment protection.

The said legislation consists of three groups of legislative acts, dealing with complex measures, natural resources, and the environment protection. The complex legislative acts determine the environment protection as a whole, i. e. without any subdivisions into individual objects of protection. The acts that are connected with natural resources determine the protection and use of separate objects of nature (e. g. Fundamentals of Land Legislation). The legislative acts related to the environment protection are aimed at precuation from the harmful influence resulting from the activity of man.

In order to determine the degree of effectiveness to which the nature protection legislation is employed, State Standards of the qualitative condition of environment have been specially elaborated. They include ecological, industrial and economic standards, those of complex use and protection. Nature protection measures are reflected in the plans of social development of cities, regions, and republics.

The Protection and Rational Use of the Earth's Depths. In the USSR the use of depths is regulated by 'The Legislation of the USSR and Union Republics Concerning the Earth's Depths'. It was adopted by the Supreme Soviet of the USSR in 1975. The law presupposes a complete and complex investigation of the depths, the complete extraction and rational use of basic mineral resources as well as those that are occurred with them, and the useful components that are contained in them; the exclusion of the harmful influence of works, conducted during the exploitation of the depths, for the preservation of reserves of certain mineral resources or the deterioration of their quality; the prevention of the pollution of earth's interior in the case of underground storage of oil, gas and other resources; the protection of air, the earth's surface, forests, waters, and other natural objects from the impact of mining, etc.

In compliance with the legislation that is now in force the mining of the deposits of mineral resources should be conducted with the help of the most rational and effective methods, which provide the completeness and complexity of the development of deposits, and minimal losses of raw materials. The complex of nature protection measures also presupposes the use of rocks of stripping or the enclosing rocks, the utilization of industrial wastes, the prevention of undesirable deformations, and the self-ignition of mineral resources and dumps.

No minor significance is attributed to the reduction of losses of mineral resources, their complex recovery and reworking. The solution of these problems helps to effectively use the unrenewed natural resources. It is not infrequent that the value of the concomitant components can be higher than that of the basic ones.

The parts of the depths presenting special scientific and cultural value are also being protected. This includes reserves of unique mineralogical, paleontological, cave and karst, eolian, and other geological objects of interest, that are usually included in preserved landscape and geological complexes.

In the Soviet Union land belongs to the State. For the exploration and prospecting of mineral resources it can be temporarily used by geological and mining organizations. In accordance with 'The Land Legislation of the USSR and Union Republics' the organizations, conducting the mining of deposits, geological exploration, construction and other works on fertile lands are supposed to make them quite suitable for the use in agriculture and forestry. The complex of measures directed at the reconstruction of disrupted territories with the aim of their further rational use is called *the recultivation of lands.*

Recultivation includes mining and technological, meliorative, agricultural activities, those connected with forestry, etc. Its implementation results in the achievement of not only partial transformation or reconstruction of the disturbed areas, but also in the creation of productive anthropogenic landscapes, which serve to improve the environment.

A very important measure connected with the preservation of lands is their protection from water and eolian erosion, the prevention of landslides, downfalls and sills, the drying of swamped soils, the filling up of ravines, the stripping of stony grounds, etc. The carrying out of these measures provides the preservation and development of land areas and the increase of their productivity.

The Protection of Water Resources and the Atmosphere. The Legislation of the USSR and Union Republics Concerning Water-handling Facilities, which has been functioning in the Soviet Union since 1971, presupposes a purposeful activity directed at protecting surface and underground waters from pollution, the redistribution of discharge, the protection of water basins and sewage waters.

A copious amount of work has been conducted on the control of sanitary conditions of water reservoirs. The protection zone is being established round water arteries. A particular attention is paid to the building of cleaning structures.

In the Soviet Union great attention is paid to the protection and rational use of underground waters, which, for a large number of populated areas, are the main source of water supply. The quality of water is controlled, measures are taken to protect the underground waters from pollution, fouling and depletion. No minor significance is attached to the protection of water resources in the regions characterized by the functioning of mining enterprises. This is where the work is being conducted to reduce the harmful impact of mining operations on the regime of underground waters, and on the reconstruction of the quality of waters that have been polluted.

The protection of the atmosphere from the hazardous impact of the productive activity of man presupposes the following measures:

(1) the perfection of now existing technological processes and the development of new ones, which exclude any emission of poisonous substances in the process of their formation;

(2) the improvement of the composition of different types of fuel: the perfection

(2) the improvement of the composition of different types of fuel, the perfection of instruments and apparatuses, the reduction or a complete disposal of various ejections into the atmosphere by means of employing cleaning constructions, and the creation of technological non-wastes processes;

(3) the prevention of the pollution of atmosphere by means of arranging the sources of air contaminators with the physical and geographical specific features of the territory taken into account;

(4) the development and rational arrangement of green plantations in cities and industrial centres, the organization of sanitary-protection zones.

The processes involving the development of the deposits of mineral resources are characterized by the intensity of air pollution. The sources of pollution are internal combustion engines of mining machines, numerous explosions during open-cast mining operations, wind erosion of the benches of quarries and rock dumps, gasification of coal quarries and mines, as well as burnings of dumps. At present the problems of eliminating the pollution of air in mines, ore pits, and quarries are to a certain extent being solved. The problem of a complete protection of the atmosphere from gas pollutions and dust still awaits its solution. It should be most emphatically stated that there can be no question of regarding any aspects of the protection and rational use of geological medium as those of secondary importance. It is a successful solution of all these problems that may well be considered to be the prerequisite on which the future of mankind depends.

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Alexander Novikov, also a graduate of the Moscow State University (1965), was one of the most outstanding members of the teaching staff in the department of geology at the Moscow Mining Institute. His scientific interests included the geology of ore deposits, physical mineralogy and petrography. He was a gifted lecturer, a methodologist, and the author of original textbooks and publications serving to establish the structure, content, and methods of teaching the basic principles of crystallography, mineralogy, and petrography. Alexander Novikov died in 1984.

Galina Popova (Cand.Sc., Geol.-Min.) graduated from the Moscow State University in 1958. She is an assistant professor of general geology and geological mapping at the Moscow Institute of Geological Exploration. She is a prominent specialist in the geology of ore deposits, geochemistry, and technological mineralogy. Her publications comprise over 80 textbooks, teaching guides, and research articles. The principal ones are devoted to the geology of copper and nickel deposits, their computer modelling, and the experimental study of sulphide magmatic systems. Popova has completely reorganized the course in 'Fundamentals of Geology' and has elaborated her own approach to the professional training of students in mining engineering.

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